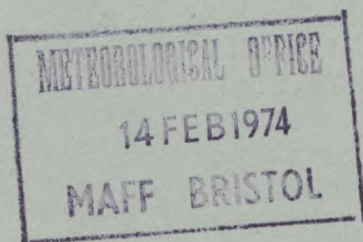


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THE IMO/WMO CENTENARY CELEBRATIONS*

By D. G. HARLEY

The completion of the first 100 years of organized international collaboration in meteorology was celebrated on 7 September 1973 in the Academy of Sciences in Vienna, the place where the first International Congress was held in 1873. A gathering of several hundred, including representatives of 73 Members of WMO and 17 other international organizations, was addressed by the Federal President of the Republic of Austria, the Austrian Federal Minister for Science and Research, the representative of the United Nations Secretary-General, and the President and Secretary-General of WMO. The ceremony in the handsome 18th Century hall was enhanced by musical interludes by the Horn Quintet of the Vienna State Opera and the Nicolai Quartet of the Vienna Philharmonic Orchestra.

In the days before the official ceremony a conference reviewing the progress of the science of meteorology was held in the International Atomic Energy Agency's modern conference room near the Vienna State Opera. In the remarkable hot dry weather of that week, with daily maxima above 30°C, the air-conditioned room was most welcome. Over 200 participants from all over the world, including many well-known figures, together with a large number of meteorologists from the services of Austria and the Federal Republic of Germany, heard and discussed a series of stimulating lectures.

Dr A. Nyberg (Sweden), past President of WMO, reviewed the history of WMO and showed some well-chosen illustrations, including one of Sir Napier Shaw in top hat and morning coat showing distinguished visitors the Stevenson screen on the 1913 equivalent of the 'Air Ministry roof'. Then Mr J. S. Sawyer (United Kingdom) brilliantly discussed the development of forecasting methods, the problems of fully employing the present flood of new types of data, and the likely line of further development. Climatology's growth from the earliest collections of data to present-day statistical and mathematical modelling was discussed by Professor H. E. Landsberg (U.S.A.): his comprehensive treatment included the input from satellite measurements and the output to all manner of human activities.

Research into climatic change was stressed by Professor R. W. Stewart

* IMO = International Meteorological Organization; WMO = World Meteorological Organization.

(Canada), chairman of the Joint Organizing Committee, who reviewed the scientific aims of the Global Atmospheric Research Programme (which he did bilingually as a good Canadian). Professor P. Morel (France), as one much involved with that multi-capability tool the meteorological satellite, spoke, also bilingually, on developments in techniques of observing the atmosphere. Finally, Professor M. Neiburger (U.S.A.) reviewed developments in weather modification and the inadequate evidence on its most important aspect, rain-making.

Each session had a different discussion leader, and the sense of the discussions was aimed at the way ahead. On the last subject, however, concern was primarily with the problem of determining the extent and strength of the scientific basis for operations here and now.

A welcome interlude in the proceedings was a whole-day excursion arranged by the Austrian authorities. The very large party was taken by coach through the lovely countryside of the Vienna Woods and the Danube Valley, with several stops for sightseeing, food and wine. The day ended with an evening in Grinzing on the outskirts of Vienna, a 'Heurigen' evening with yet more food, music and wine offered by WMO.

After the weekend the participants reassembled in Geneva, the home of WMO, in the new Geneva International Conference Centre. Here, after a brief centenary ceremony, there was a two-day conference on the economic and social benefits of meteorology run on similar lines to the Vienna one.

As hors d'œuvre Mr O. Reverdin of the Swiss National Council for Research philosophized on the function of the State in respect of scientific research. Academician V. A. Bugaev (U.S.S.R.), one of the original planners of World Weather Watch, discussed its impact on economic and social development. Next day Mr S. Tewungwa of East Africa spoke of the nature and value of WMO assistance to developing countries, and was followed by Professor E. Bernard (Belgium) on the role of meteorological services in economic and social development, relatively greatest where they are weakest, in developing countries. Finally, Mr R. H. Clark (Canada) described the importance of the interface between meteorology and hydrology to water development, with a rapidly growing world demand for water, and Mr P. J. Meade (United Kingdom) described the growth from meteorology's early involvement with marine affairs up to its present close relationship with oceanography, and the future prospect that the two disciplines should increasingly be regarded as one. As in Vienna, there was discussion on each lecture, but time was short for adequate comment on such wide-ranging subjects.

The final item of the whole celebrations was an evening steamer trip with dinner and music on Lake Geneva, offered by the Swiss authorities. On a calm clear evening some hundreds of participants and their wives thoroughly enjoyed themselves on board. The air of camaraderie usual on international meteorological occasions was fully in evidence.

The whole programme was presided over by Mr M. F. Taha, President of WMO. A number of former IMO Prize winners took part, including Sir Graham Sutton, and most Members were represented by the Directors of their Meteorological Services, and, in many cases, by their Ambassadors as well. By decision of the Executive Committee, the lectures presented at both conferences will be published in the four official languages of the Organization (English, French, Russian and Spanish).

CENTRAL ENGLAND TEMPERATURE QUINTILES AND ASSOCIATED PRESSURE ANOMALIES ON A MONTHLY TIME-SCALE

By R. MURRAY and J. D. LANKESTER

Summary. The climatological association between temperature quintiles in central England and pressure anomaly patterns over the northern hemisphere on the monthly time-scale are presented. For the two extreme quintiles the circulation patterns are generally opposite in type. The characteristic seasonal changes of pressure anomaly patterns associated with temperature quintiles are discussed.

Introduction. Quintiles of monthly mean temperature in central England (see Manley¹ and Murray²) are commonly employed in long-range weather forecasting in the Meteorological Office. Maps which show the field distribution of monthly mean pressure anomaly over most of the northern hemisphere typically associated with each temperature quintile for each month of the year are available. These maps form the basis of this descriptive account of the main features of the anomalous atmospheric circulations which are climatologically characteristic of the temperature quintiles throughout the year. A particular temperature in an individual month can, of course, arise from a variety of circulation types. However, there tends to be a typical circulation associated with each of the different temperature quintiles, especially for the extreme quintiles 1 and 5, and the climatology of these mean circulations is of some interest.

In the present note the monthly mean pressure averages refer to the period 1873-1968, and the quintile boundaries of monthly mean temperature in central England are as given by Murray.²

Mid-season monthly pressure anomaly patterns. Skeleton maps of composite monthly mean pressure anomaly patterns for temperature quintiles 1 (= very cold) and 5 (= very warm) are depicted in Figures 1-4, which refer to January, April, July and October respectively.

The striking feature of Figure 1(a) is the very large-scale blocking signified by the positive anomaly centre (PAC) greater than 10 mb over Iceland and the negative anomaly centre (NAC) less than minus 4 mb over Spain typically associated with very cold weather (quintile 1) in central England in January. Very cold weather in central England in the other mid-season months is also typically associated with blocking over the north-east Atlantic, but the high-latitude PAC weakens to a minimum in July (Figure 3(a)) and the NAC which was over Spain in January (Figure 1(a)) weakens a little and drifts northwards to southern Sweden in July. For the quintile 1 case the very strong easterly anomaly of flow over Britain (associated with above-average pressure) in January backs to north-west to north (with below-average pressure) in July.

In the quintile 2 (cold) cases the main PACs and NACs are generally weaker than the corresponding anomaly centres in the quintile 1 classes in all mid-season months; this indicates the greater variability of pattern which contributes to quintile 2, compared with the variability of pattern which contributes to quintile 1.

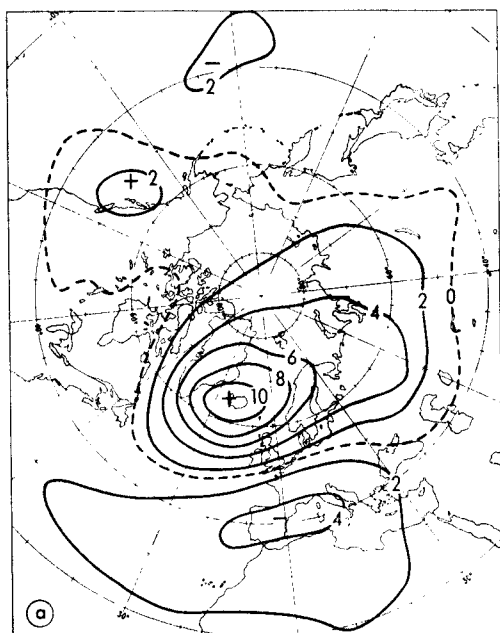


FIGURE 1(a)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 1 JANUARYS IN CENTRAL ENGLAND (IN MILLIBARS)

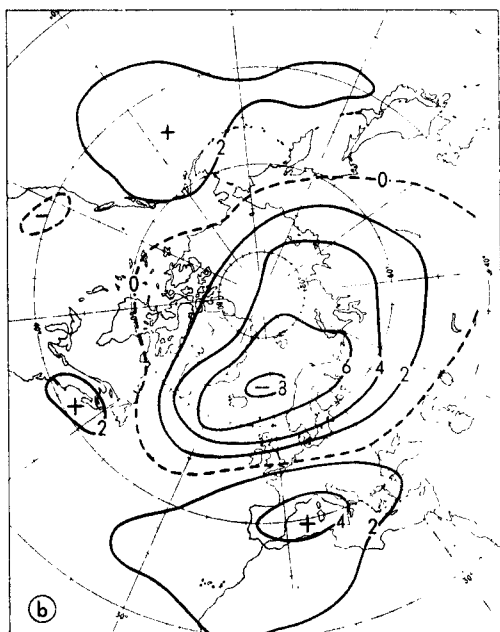


FIGURE 1(b)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 5 JANUARYS IN CENTRAL ENGLAND (IN MILLIBARS)

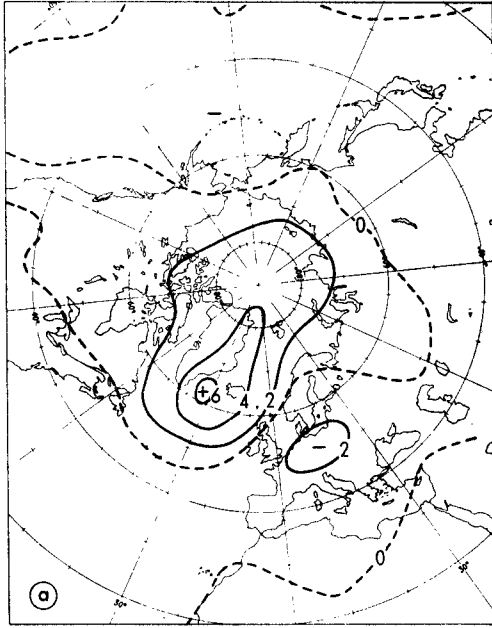


FIGURE 2(a)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 1 APRILS IN CENTRAL ENGLAND (IN MILLIBARS)

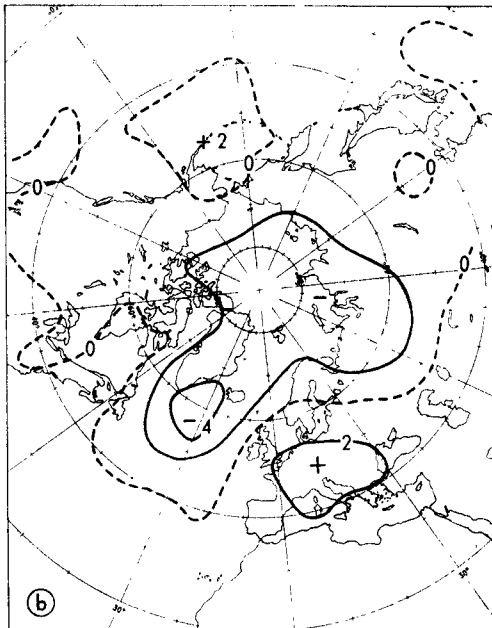


FIGURE 2(b)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 5 APRILS IN CENTRAL ENGLAND (IN MILLIBARS)

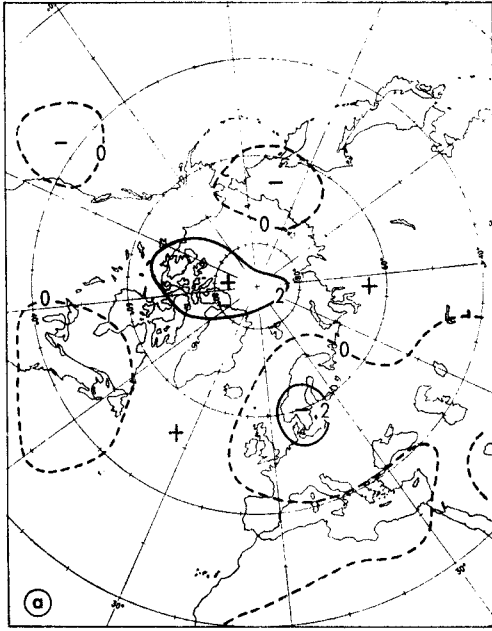


FIGURE 3(a)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 1 JULYS IN CENTRAL ENGLAND (IN MILLIBARS)

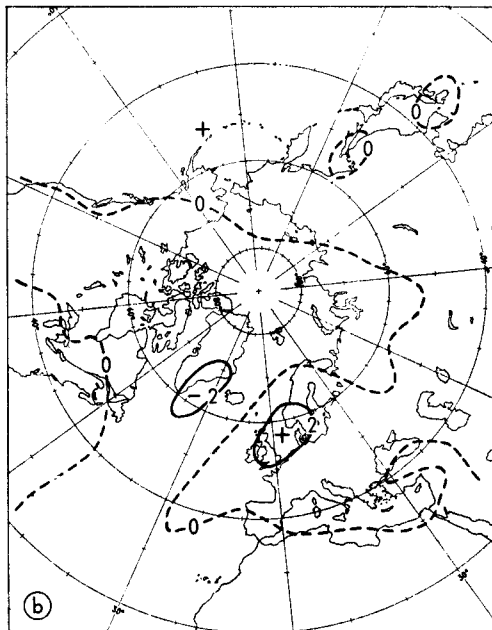


FIGURE 3(b)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 5 JULYS IN CENTRAL ENGLAND (IN MILLIBARS)

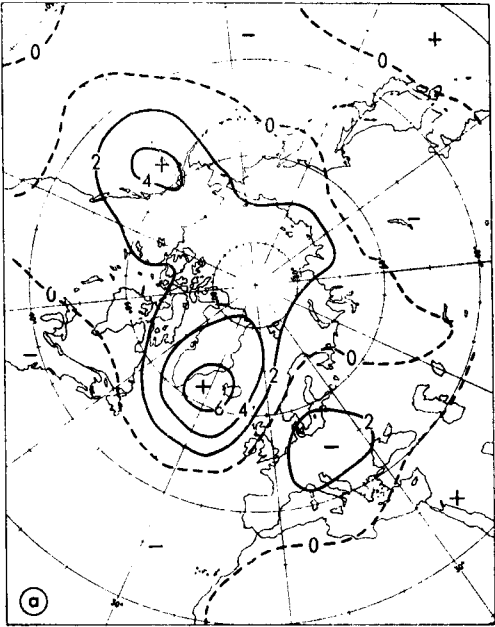


FIGURE 4(a)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 1 OCTOBERS IN CENTRAL ENGLAND (IN MILLIBARS)

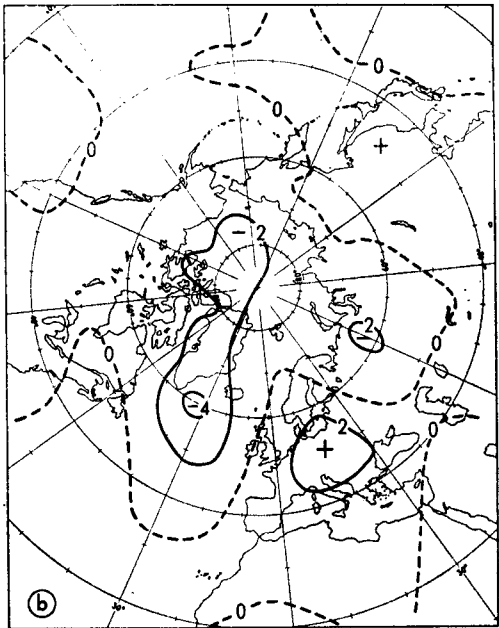


FIGURE 4(b)—COMPOSITE MONTHLY MEAN PRESSURE ANOMALY MAP IN SKELETON FORM FOR QUINTILE 5 OCTOBERS IN CENTRAL ENGLAND (IN MILLIBARS)

The very warm (quintile 5) January is typically associated with the mean pressure anomaly pattern of Figure 1(b) which shows a very progressive pattern in the Atlantic-European sector, as suggested by a strong NAC in the Norwegian Sea and a PAC in the western Mediterranean. In the other mid-season months the main NACs and PACs in the Atlantic-European sector are weaker than in January. The most interesting feature, however, is the shift of the NAC from the Norwegian Sea in January to near south-east Greenland in July and to off south-west Iceland in April and October, whilst the main PAC shifts from the western Mediterranean in January to central Europe in April and to the North Sea in July, then returns to central Europe in October.

The composite anomaly patterns for the quintile 4 (warm) class are generally weaker than for quintile 5, and this indicates greater variability of pattern in the former case.

Locations of main anomaly centres throughout the year. The positions of the main PACs and NACs each month typically associated with temperature quintiles 1, 2, 4 and 5 are plotted in Figure 5(a)–(d). In these diagrams the main anomaly centres which are necessary to depict the significant features of the pressure anomaly patterns are indicated. PACs are shown as crosses and NACs as dots and the adjacent figures give the month (1 = January, 2 = February, etc.). In winter the absolute values of anomaly centres are much stronger than in summer, as may be seen by comparing Figure 1 with Figure 3.

A cursory examination of Figure 5(a) shows that the North Atlantic PACs for all quintile 1 months except June are clustered near Iceland, with the corresponding NACs scattered over the Atlantic between 35° and 45°N and over Europe but clustered near southern Scandinavia in the summer months. There is also a tendency for PACs to be grouped over the Siberian Arctic in the summer and early autumn, but the NACs are widely scattered over the North Pacific and eastern Asia. In Figure 5(b) (quintile 2) the PACs for all months except June are in the North Atlantic between 45° and 65°N with the NACs over Europe and the central Mediterranean. Whereas it may be inferred from Figure 5(a) that the quintile 1 months tend to be associated with east or north-east anomalies of flow over Britain, it is clear from Figure 5(b) that quintile 2 months are usually associated with north-west or north anomalies of flow.

In the quintile 5 (very warm) case shown in Figure 5(d) there is a cluster of NACs near Iceland (compared with the PACs in a similar region in Figure 5(a)) and PACs are clustered near southern Scandinavia from May to September but mostly in or near the central Mediterranean in other months. In this case there is evidently a marked tendency for a south-east anomaly of flow over Britain in the five summer months and mostly a south-west anomaly of flow at other times of the year. Away from the Atlantic-European sector there is, in Figure 5(d), a group of NACs near the Kara Sea (to the east of Novaya Zemlya), mostly in summer and autumn, and a preponderance of PACs in the North Pacific east of 180°W. It is also noteworthy in this diagram that the PACs and NACs are often located in broadly similar geographical areas to the NACs and PACs respectively in Figure 5(a) in corresponding months; in other words Figure 5(d) is rather like Figure 5(a)

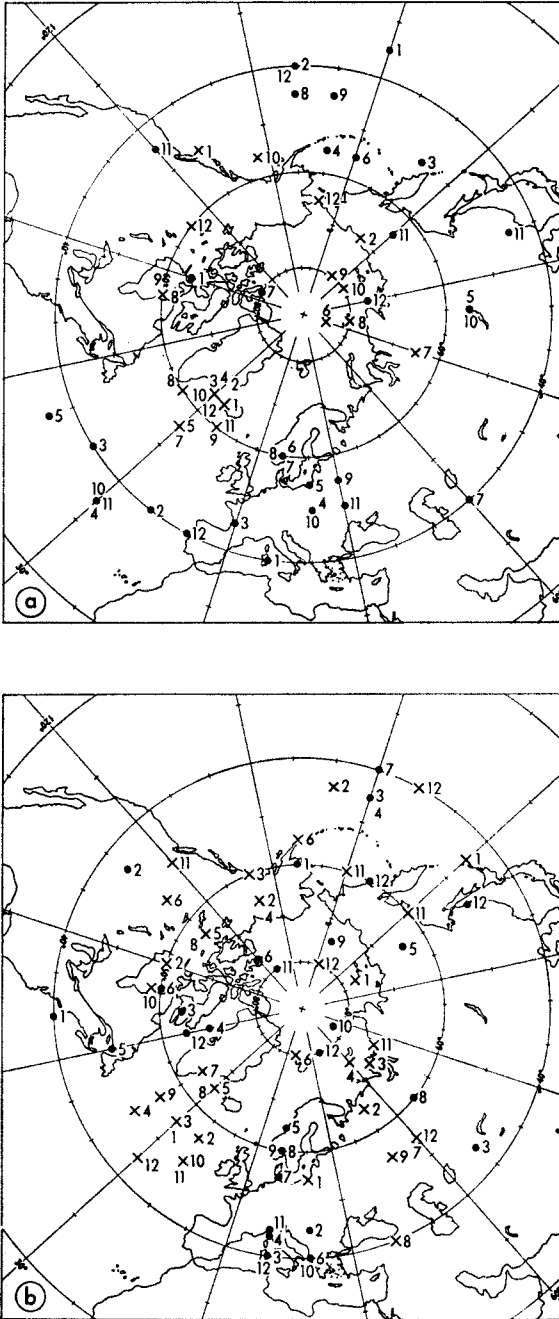


FIGURE 5—POSITIONS OF THE MAIN POSITIVE ANOMALY CENTRES (PACs) AND NEGATIVE ANOMALY CENTRES (NACs) FOR EACH MONTH

x PAC; • NAC; 1 January, 2 February, etc.

(a) associated with composite map for 'very cold' or quintile 1.

(b) associated with composite map for 'cold' or quintile 2.

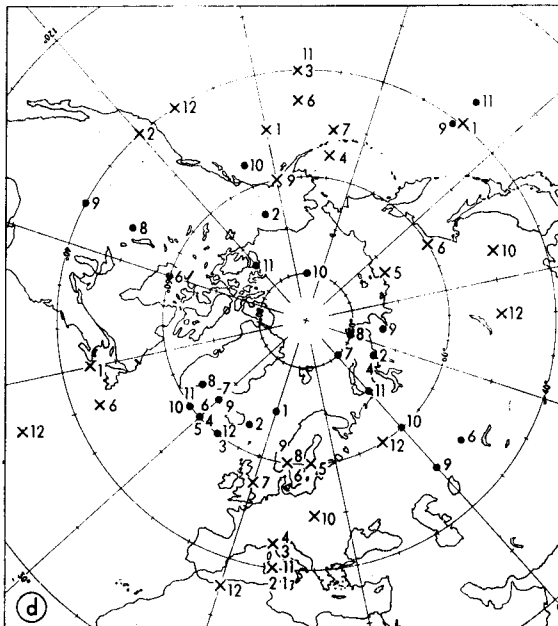
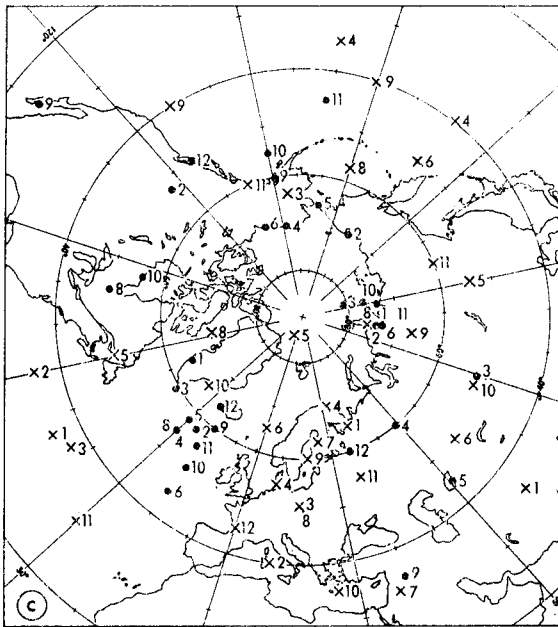


FIGURE 5—*continued*

- (c) associated with composite map for 'warm' or quintile 4.
- (d) associated with composite map for 'very warm' or quintile 5.

with the signs of the anomaly centres interchanged. In the quintile 4 or warm case, shown in Figure 5(c), there are clearly rough similarities in the positions of the PACs and NACs compared with the distribution of the anomaly centres shown in Figure 5(d) (quintile 5). However, it is noticeable in Figure 5(c) that the NACs in the Atlantic are not so closely clustered together as in Figure 5(d). It is also interesting to observe that Figure 5(c) (quintile 4) resembles Figure 5(b) (quintile 2) with the signs of the anomaly centres reversed.

Seasonal variation of monthly pressure anomaly. In Figure 6(a) is shown the monthly mean pressure along the Greenwich meridian during the year, whilst the variations of monthly mean pressure anomaly associated with the composite anomaly maps for the extreme temperature quintiles (quintiles 1 and 5) are shown in Figures 6(b) and 6(c). It is noteworthy that the high-latitude positive anomaly (PA) in Figure 6(b) — the very cold case — is greatest near 70°N in midwinter and at a minimum near 80°N in late summer, whilst the negative anomaly (NA) in low latitudes also appears to move to higher latitudes by the end of the summer; in the latitudes of the British Isles there is clearly a strong easterly anomaly of flow in winter associated with marked anticyclonic blocking, but in the summer the low temperature is associated with below-average pressure (i.e. with cyclonic weather types). Figure 6(c) — the very warm case — shows a pattern which is like that in Figure 6(b) with the signs of the anomalies reversed; in particular over Britain there is a westerly anomaly of flow in winter and above-average pressure (i.e. anticyclonic weather types) in summer.

Figure 7(a) gives the monthly mean pressure along latitude 55°N during the year. In Figures 7(b) and 7(c) are shown the seasonal variations of monthly mean pressure anomaly, associated with the composite anomaly maps for the extreme temperature quintiles, along 55°N . Once again it is evident that Figure 7(b) (very cold case) is like Figure 7(c) (very warm case) with the signs of the anomalies reversed. In Figure 7(b) the main positive pressure anomalies are in the central Atlantic each month, with the smallest anomalies in the summer; negative anomalies are generally east of 10°W over the European sector except in January and February. Clearly very cold weather in central England is generally associated with a northerly component of anomaly flow in most months but particularly in spring and autumn. In contrast, in Figure 7(c) below-average pressure generally occurs in the Atlantic and above-average pressure over Europe, with a southerly component of anomaly flow over or near Britain.

Finally, in Figure 8 the pressure anomaly and direction of the anomaly flow at the grid point $55^{\circ}\text{N } 00^{\circ}$ for each quintile of temperature throughout the year are conveniently tabulated. The seasonal variation of the local circulations near central Britain, typically associated with the different quintile classes, can be seen at a glance and related to the large-scale circulation described in the other figures. It must of course be remembered, as mentioned in the Introduction, that a specific month may have a temperature/circulation association which is quite untypical of the climatological relationship, particularly with quintiles 2, 3 and 4.

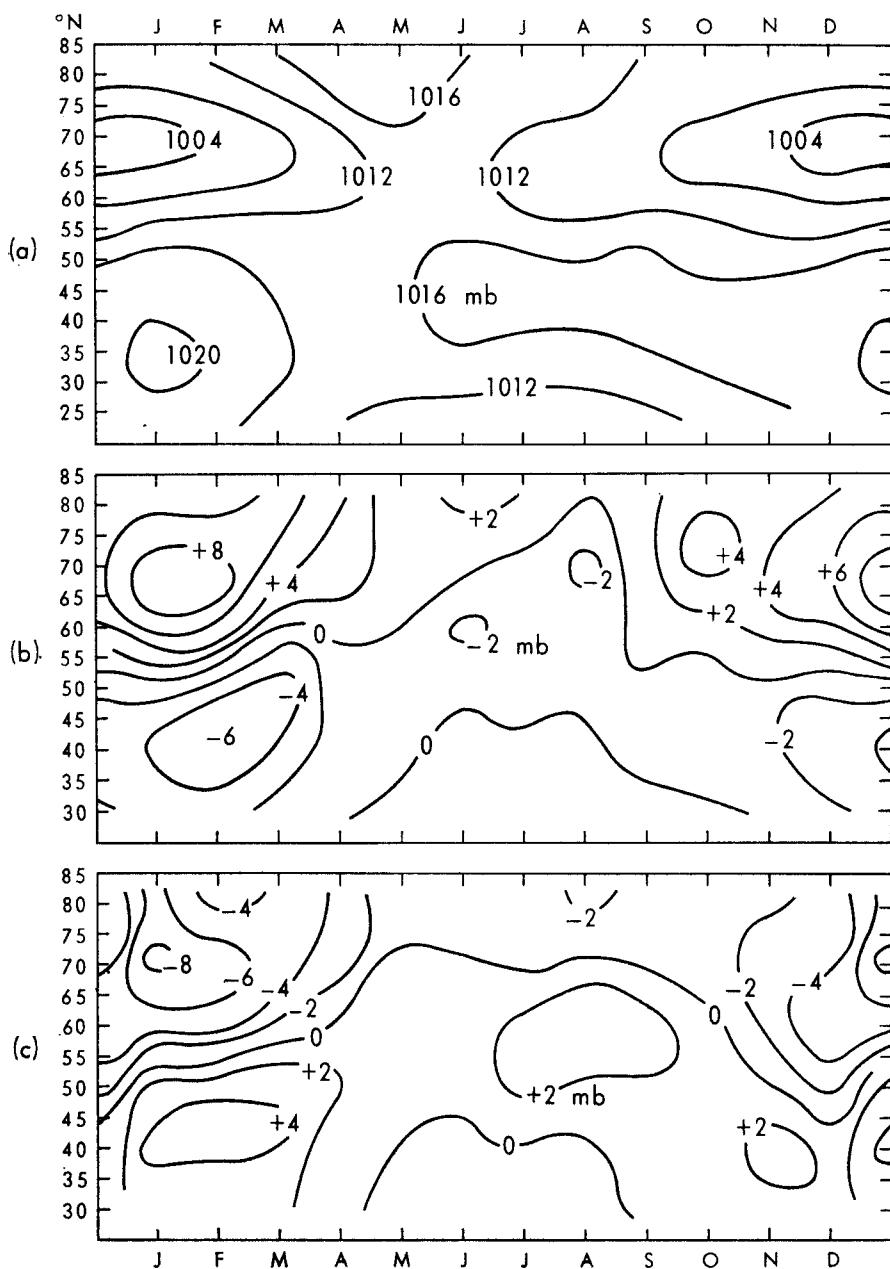


FIGURE 6—CONTINUITY DIAGRAMS ALONG THE GREENWICH MERIDIAN

(a) monthly mean pressure (1873-1968); (b) monthly mean pressure anomaly associated with composite map for quintile 1 temperatures in central England; (c) monthly mean pressure anomaly associated with composite map for quintile 5 temperatures in central England.

Notes. For convenience in presentation isobaric isopleths are drawn smoothly from the discrete monthly data.

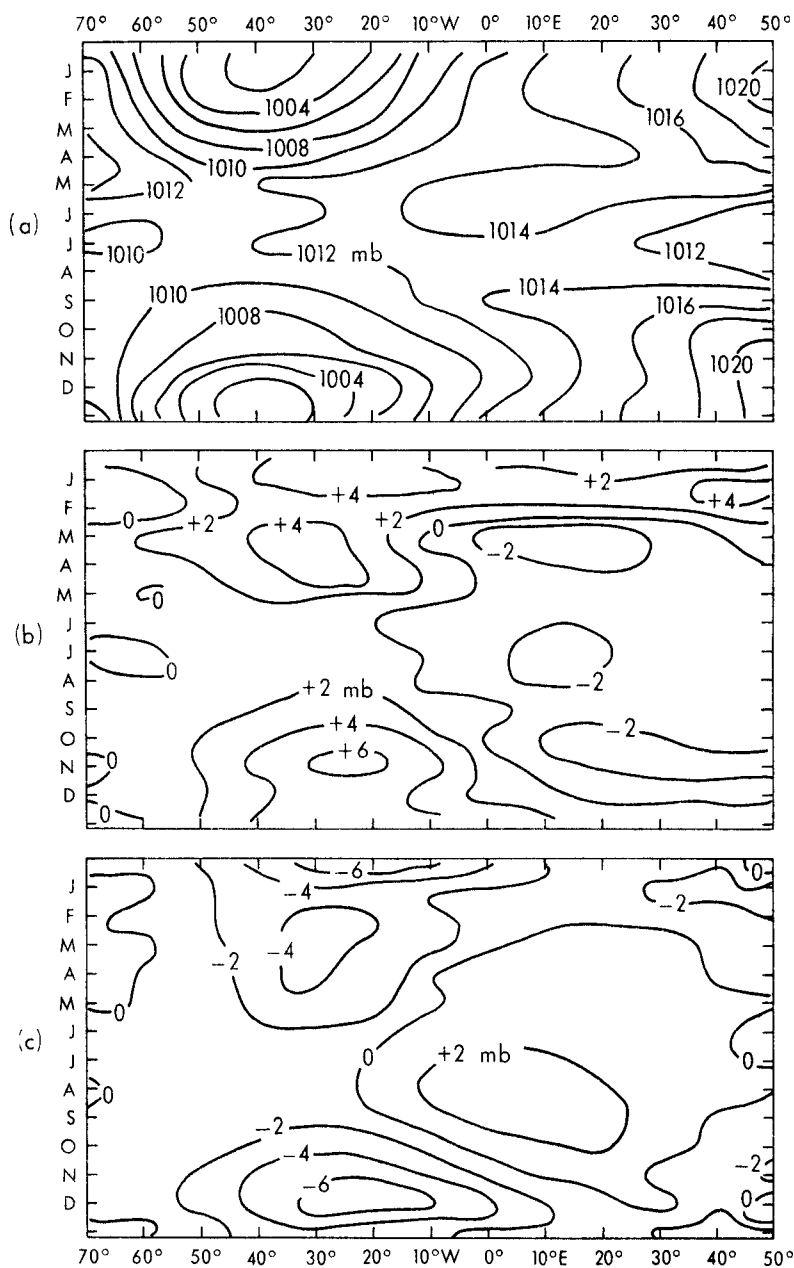


FIGURE 7—CONTINUITY DIAGRAMS ALONG LATITUDE 55°N

(a) monthly mean pressure (1873-1968); (b) monthly mean pressure anomaly associated with composite map for quintile 1 temperatures in central England; (c) monthly mean pressure anomaly associated with composite map for quintile 5 temperatures in central England. See note in caption to Figure 6.

	J	F	M	A	M	J	J	A	S	O	N	D
1 Very cold	↖ +3.3	↖ +1.9	↘ -2.7	↘ -0.6	↘ -0.5	↗ -1.7	↓ 1.6	↘ -1.8	↘ +0.2	↘ -0.4	↓ +1.6	↘ +1.0
2 Cold	⊕ +1.1	↘ -0.2	↖ +0.5	↖ -0.2	↘ -0.4	↖ -0.4	⊙ -1.4	⊙ -1.5	↘ -1.5	↓ +1.5	• +0.1	↘ +0.9
3 Average	↓ -1.0	⊕ +2.2	↘ +1.3	⊙ -0.9	↗ -0.2	→ +0.8	↗ -0.8	→ -0.3	→ -1.2	↗ -0.5	↖ +1.3	↗ +0.3
4 Warm	↗ -1.5	↗ -2.6	↗ +1.0	↗ +0.4	↑ -0.1	↖ +0.4	↖ +1.3	↑ +0.3	↖ +0.1	↑ -1.4	↗ -1.5	→ +1.3
5 Very warm	→ -1.4	↗ -1.6	↗ +0.6	↗ +1.2	↖ +1.3	↖ +1.1	⊕ +2.8	↖ +3.3	↖ +2.6	↗ +0.7	↗ -1.4	↑ -4.4

FIGURE 8—MONTHLY MEAN PRESSURE ANOMALY IN MILLIBARS AND DIRECTION OF ANOMALY FLOW AT 55°N 00° FROM COMPOSITE MAP FOR EACH QUINTILE OF MONTHLY MEAN TEMPERATURE IN CENTRAL ENGLAND

Ill-defined directions are indicated as a dot when associated with a col pattern, and as an encircled dot or cross when associated with cyclonic or anticyclonic patterns respectively near 55°N 00°.

REFERENCES

1. MANLEY, G.; The mean temperature of central England 1698-1952. *Q J R Met Soc*, London, 79, 1953, pp. 242-261.
2. MURRAY, R.; A note on central England temperatures in quintiles. *Met Mag*, London, 99, 1970, pp. 292-294.

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THE USE OF NUMERICAL FORECASTS

By T. H. KIRK

Summary. The use of numerical forecasts is illustrated by procedures at the Central Forecasting Office, Bracknell and an attempt is made to define the legitimate role of subjective interpretation.

Introduction. In a recent paper Brown and Fawcett¹ have illustrated both numerical and subjective procedures in use at the National Meteorological Center (NMC), Washington, with particular emphasis on the 'man-machine mix'. They stressed three important conclusions:

- (a) that the meteorologist produces the best forecast by careful and systematic use of numerical guidance as opposed to independent forecasting in competition with the computer product;
- (b) that the meteorologist's average forecast skill improves in direct proportion to the improvement in numerical forecast guidance that he uses; and
- (c) that the better the numerical prognosis, the more difficult it is to improve manually with any degree of success.

This note also deals with aspects of the use of numerical products and the extent to which these should be accepted at face value or as guidance

material. The content is based on experience at the Central Forecasting Office (CFO), Bracknell and on the procedures in use there, but some attempt is made to view the problem in terms of general forecasting.

The subject is considerably simplified if the essential role of the forecaster is correctly appreciated.

The function of the forecaster. The forecaster is concerned in general with the interpretation and forecasting of events over the whole gamut of weather processes. His field of activity extends over the vast number of observations, both subjective and instrumental, available at synoptic hours, together with an increasing variety of asynoptic observations from aircraft and satellites. For the efficient handling of such a quantity of data it has become necessary to use methods of data processing, analysis and forecasting based on the computer, and these will improve progressively both in scope and in accuracy. The forecaster's essential role is the exercise of discrimination or judgement within the context of the available information and the needs of his customers. In the 'man-machine mix', the advantages of the computer as a calculator and data processor are combined with the human ability to exercise judgement. If some justification of this position is required, it may be sufficient to point out the severe limitations of the human being as a calculator and data processor; on the other hand, only the human brain can exercise judgement in the complex situations with which the forecaster is concerned.

To solve his particular problem the forecaster may have available :

Numerical products.

- (a) A variety of computer products based on different models, e.g. barotropic or baroclinic, filtered or primitive-equation, 6-level or 10-level, dry or moist.
- (b) Computer products on different scales, e.g. octagon model (large-scale), rectangle model (fine-mesh).
- (c) Products from different World Meteorological Centres, Regional Meteorological Centres or National Meteorological Centres, obtained through World Weather Watch.

Additional observations.

- (a) Local observations, e.g. for local forecasting.
- (b) Special observations, e.g. sferics, radar, for mesoscale forecasting.
- (c) Observations at a time later than that on which the computer products are based.
- (d) Satellite observations, e.g. automatic picture transmission (APT) photographs.

Special knowledge. Additionally, for any particular model, the forecaster may know :

- (a) The data deficiencies of the model, i.e. whether the analysis is a good one or is deficient in some essential feature.
- (b) The model deficiencies, i.e. the extent to which significant physical processes are either not incorporated or are inadequately represented in the model.

- (c) The existence of systematic mathematical inaccuracies, e.g., truncation errors.
- (d) The performance as determined by evaluation studies; in particular, the existence of systematic errors.
- (e) The existence of geographical or seasonal errors.

Theoretical and empirical knowledge. The forecaster has a background of theoretical and empirical knowledge much of which is not incorporated in the forecast models and which can be used in particular circumstances. He is also acutely aware of the different scales of meteorological events and of the limitations of models particularly in relation to most features of weather as distinct from the analytical parameters associated with the large-scale circulation.

The relevance of much of this information depends on the particular problem under examination, as does the forecaster's attitude. The extent to which judgement is exercised varies with the particular need. The fundamental principle is that objective methods should be used to the fullest extent compatible with the requirement so that judgement can be more effectively exercised at a higher level. It is unnecessary for expert judgement to be employed in circumstances where routine objective techniques can be used to provide an adequate service. Forecast verification has an obvious part to play in furthering this approach.

Procedures at CFO, Bracknell. Procedures at CFO, Bracknell, may be used to illustrate some features of the above remarks and to emphasize the complex interplay of subjective and objective aspects in forecasting.

Intervention. The term 'intervention', some aspects of which are described as 'bogusing', is used to describe the process whereby the forecaster modifies the data available to a forecast model. It includes :

- (a) The early scrutiny of selected data and the rejection or correction of observations. This is additional to the quality-control procedures used in the computer.
- (b) Monitoring the objective analysis and taking action to correct the background field which provides the basis for the next analysis. Intervention incorporates the subjective influence of the forecaster at an early stage in the forecast process and at present is an essential element in operational forecasting.

Subjective 24-hour surface prognoses. Numerical forecasts (for 1000 mb, 500 mb, 300 mb, 1000-500-mb thickness and of thermal vorticity), are used by the Senior Forecaster in the preparation of his 24-hour surface prognoses. On two occasions per day, in the preparation of forecasts for 06 GMT and 18 GMT, the numerical guidance constitutes a 30-hour forecast, whereas numerical guidance for the 00 GMT and 12 GMT forecasts is for 36 hours in advance. The forecaster modifies the 1000-mb numerical forecast on the following grounds :

- (a) That he has some knowledge of the limitations of the analysis on which the forecast was based and of the forecast model itself.
- (b) That he has later data.
- (c) That he wishes to incorporate significant features of a smaller scale than can be expressed by the forecast model, e.g. fronts, polar lows.

As a result of the enforced timing of operational requirements in relation to the twice-daily issues of computer forecasts, the guidance for a 24-hour forecast represents a 30-hour or 36-hour forecast from the computer. Direct comparison of the performance of 24-hour subjective and numerical forecasts is therefore neither realistic nor significant for the operational need.

Medium-range forecasts. Forecasts for two and three days ahead are produced daily in which numerical forecasts are used as a basis. The forecasts used are CFO numerical prognoses at 1000 mb and 500 mb for 48 hours and 72 hours and the United States NMC prognoses at 500 mb for 48 hours and 72 hours. German prognoses are also occasionally consulted.

Subjective prognoses for 48 hours and 72 hours are produced by modifying the computer products where necessary. This modification has as its basis knowledge of :

- (a) Model deficiencies.
 - (1) The systematic error, characteristic of numerical forecasts, in the eastwards progression of troughs and ridges, i.e. phase lag.
 - (2) The lag in the change of amplitude of wave features.
 - (3) The inadequate representation of cyclogenesis.
- (b) Analysis deficiencies, where known, e.g. of the CFO model.
- (c) Later data.

The forecaster critically compares the corresponding prognoses of the different numerical models available to him in the light of :

- (a) Continuity of events in the real atmosphere.
- (b) Continuity in the performance of the different models.
- (c) Known characteristics.

His final subjective version may be based on a particular numerical model, suitably modified, or may be a compromise between different solutions. Evaluation has shown that the subjectively modified forecasts are an improvement on the numerical forecasts from any particular model. The fact that the subjective element is of real significance has been shown by a decision to use a minimum number of selected forecasters on this task. A marked improvement in performance was achieved by the implementation of this decision.

Aviation forecasts. Forecast information for route planning at all upper levels is issued directly from the numerical model and is unmodified. Evaluation has shown that no systematic improvement can be achieved in practice by subjective modification.

For briefing aircrew, however, forecast charts at 200 mb, 250 mb, 300 mb, 500 mb, and of tropopause and maximum wind are prepared by subjectively modifying numerical forecasts. The argument for this procedure rests on

the need for providing more-precise information on jet streams and detailed structure at the tropopause. The advantages are marginal and it is a matter of opinion whether they justify the additional effort involved.

Here, then, is an area where subjective modification, although perhaps justifiable for some purposes at present, will probably be unprofitable in future. This illustrates the necessity for adopting a pragmatic attitude towards the satisfaction of forecast requirements.

General forecast practice. The forecaster at an outstation who has to use numerical products is in general in a much weaker position to judge their adequacy than the forecaster at CFO. The following notes illustrate possibilities :

Manual monitoring of objective analysis. It cannot be assumed that the objective analysis received from some large forecast centre incorporates all the data available, and the forecaster should examine it in relation to the data, particularly late data in the area with which he is concerned. The basic object is to sharpen the analysis by examining known or suspected areas of uncertainty. The checks should include :

- (a) Positions and depths of low-pressure centres.
- (b) Positions and sharpness of troughs and ridges.
- (c) Identification of zones of steep gradients, e.g. jet streams on upper-level charts.
- (d) Absolute values of individual isopleths.

The obvious method of checking consists in the plotting of significant observations on a copy of the analysis chart. Amendments can then be made as necessary.

Manual monitoring of numerical forecasts. Numerical prognostic charts are available to most forecasters and are a useful and necessary basis for practical forecasting. They have, however, certain inherent deficiencies which make them less accurate, and hence less useful, than they could otherwise be. These deficiencies may arise :

- (a) From an analysis which is inadequate for its purpose, in general owing to insufficient or badly distributed data at the time of preparation.
- (b) From the inability of the model accurately to represent all the different types of development which can occur in the real atmosphere.
- (c) From the inevitable mathematical inaccuracies in calculation, e.g. truncation errors.

These considerations provide the justification for attempting to modify and improve numerical forecasts. The modified product may or may not be more accurate in general statistical terms than the original numerical forecast because manual modification inevitably introduces its own inconsistencies, but the ultimate justification is that it can be more suited to its particular purpose. For normal flight-planning purposes, the automated upper-air chart is adequate; as a briefing aid for the information of pilots more detail may be required and manual modification can be used to emphasize the positions and strengths of jet streams and the details of the wind and temperature fields at flight levels.

Surface numerical forecast charts require routine modification to show small-scale synoptic detail and frontal structure significant for weather events. Whether considered in relation to upper-air charts or to surface charts, the forecaster's function cannot be visualized solely as one of error removal. There is of course this aspect, and it is most important; additionally, however, there is the necessity of adding small-scale detail of real practical significance, particularly as concerns the surface forecast. The techniques for doing this are the traditional subjective forecasting methods.

The following remarks relate to elements of bias and error which are sufficiently systematic to be noticed by forecasters in day-to-day contact with numerical forecasting products :

(a) Over data-sparse areas in general, and ocean areas in particular, satisfactory analysis depends disproportionately on the reception of a few critical observations, e.g. those from ocean weather ships. If one or more of these is missing (e.g. late or rejected) then the analysis, and also the subsequent forecasts, may be appreciably in error. The forecaster may be in possession of these observations at the time of reception of the forecast and will be in a position to judge to what extent the forecast would have been different, had the missing observations been available at the time of analysis.

Even when critical observations are available, it may happen that in a rapidly developing situation the computer will not react realistically and sufficiently quickly to the new observations on account of the inhibiting effect of the background field. The discerning forecaster will be aware of this possibility and will be prepared to face the necessity of making appropriate adjustments to the forecasts.

The problem of 'updating' is also relevant. Numerical charts are produced on a twice-daily cycle whereas most forecast requirements are based on six-hourly intervals. Intermediate surface observations are always available and they occasionally indicate the beginnings of rapid changes which have not adequately been taken into account in the computer forecasts.

(b) Models in use in numerical forecasting are of different degrees of sophistication in that they attempt to take account of different physical processes to a lesser or greater extent. If some physical process is not included in the model, then the numerical forecast is necessarily deficient in this respect. Of more importance to the forecaster is the fact that nominal inclusion of some physical process in the model is no guarantee that this process will be handled effectively or that the results will be at all realistic. Forecasters should know the details and basic assumptions of the different models in current operational use, so that they are not led to expect too much in any particular circumstances. The limitations of most numerical models are in general carefully stated before they are introduced into operational practice. Once in use, these limitations are often conveniently forgotten, and the models tend to be used beyond the limits for which they were designed.

(c) As mentioned earlier, most numerical models are subject to phase error, are somewhat inadequate in their treatment of rapid changes of wave amplitude, and are unable to handle small-scale cyclogenesis at all realistically.

There is therefore plenty of scope for the manual refinement of numerical products, but it is worth emphasizing that manual methods of adjustment should be based on recognized statistical and synoptic methods of assessment.

The forecaster's normal background of experience is a poor substitute for objective tests, and the amendment of numerical prognoses cannot be justified on this basis alone. Objective knowledge of the behaviour of each model in an operational context must be obtained in a systematic way. Vague subjective impressions are not a sufficient basis for action.

Conclusion. Throughout this account, a situation has been envisaged in which the forecaster has access to sources of information and theory additional to the available computer products. It is this additional information and knowledge which provide the basis and the justification for his attempts to modify any numerical forecasts. In practice, only he can decide the extent to which he is justified; for certain purposes and in certain situations he may know from evaluation studies that the numerical product already satisfies the operational need and hence that modification would be unnecessary. In other instances it may be known that subjective modification, although inherently desirable, is ineffective in practice. Some requirements, particularly those concerned with detailed distributions of weather elements in space and time, may demand that the forecaster use the numerical products as guidance only, basing his final forecasts partly on the automated products and partly on additional data, empirical knowledge and theoretical considerations extraneous to them. It must be remembered that most models are based on relatively few analytical parameters and that a vast amount of data is not utilized. This extra-model information, although perhaps of little relevance to large-scale atmospheric circulation, may be vital for a local problem.

In considering the conclusions of Brown and Fawcett, cited above, the meteorologist produces a better forecast by using the automated products as a basis because they are derived objectively, by known mathematical procedures, from well-established physical principles. Within the limitations of the physical model there is no different method capable of providing a better basis. Numerical models, like all other physical models, must be tested and evaluated. Known limitations provide a means of improvement either by subjective modification or, better still, by improvements to the model itself. Improvements to the numerical model entail a diminishing possibility for further subjective criticism. The area of subjective modification progressively diminishes, but this does not render the forecaster any the less necessary. Forecast periods are being extended in time and there will always be demands at the margin of the capability of present models offering scope for subjective criticism and forecast modification. The development of meso-scale models is only in its infancy and subjective interpretation and forecast modification have an even more important role to play in this field. Interpretation, on which any forecast modification must be based, implies the application of theoretical knowledge and information not intrinsic to the model under consideration. With the ever-present tyranny of detail it is difficult to envisage either a time or a situation when the forecaster will not be able to make valuable contributions to at least some forecast products.

REFERENCE

1. BROWN, H. E. and FAWCETT, E. B.; Use of numerical guidance at the National Weather Service's National Meteorological Center. *J Appl Met, Lancaster, Pa*, 11, 1972, pp. 1175-1182.

LARGE CHANGES IN WIND PATTERNS AT SEA

By WAYNE V. BURT, TIMOTHY CUMMINGS and CLAYTON A. PAULSON
(School of Oceanography, Oregon State University, Corvallis, Oregon, U.S.A.)

Summary. Diurnal variations in the wind over the North Atlantic were observed in September 1972. There were unexpectedly large changes in the character of these variations over relatively short distances.

Introduction. Burt *et alii*^{1,2} found great regularity in the diurnal cycles of wind velocity in two studies of wind velocity over the ocean near the coast. Both studies were made from records for periods somewhat shorter than two weeks during the season of the year when the wind was relatively steady in direction. The areas studied were areas of strong oceanic upwelling, one off the coast of Peru and the other off the coast of Oregon.

An opportunity arose to see if the same sort of variability existed over the open ocean in mid latitudes during Operation JASIN (Joint Air Sea Interaction) 1972, which was sponsored by the Royal Society and took place in the North Atlantic west of Ireland near Ocean Weather Station J (52° 30' N, 20° 0' W) during the month of September 1972.

Method. Data were taken from cup anemometers mounted on four buoys located as shown in Figure 1. Wind speed and direction were recorded at 10-minute intervals for the same 12·7 days on all four buoys. In Burt *et alii*^{1,2} the co-ordinate systems were defined by the coastline, and the variability was studied of both the long-shore and onshore components of the surface wind. For the JASIN wind study, in the absence of a coastline, the *u* component was taken as positive to the east, and the *v* component positive to the north. Hourly averages of *u* and *v* were taken for each hour of the day during the study period. Values for each hour of the day were then averaged for the study period, this process resulting in four sets of 24 pairs of values of *u* and *v*, one set for each buoy. A sinusoidal curve with a 24-hour period was fitted by means of a least-squares technique to each of the data sets. Then for each hour of the day pairs of *u* and *v* fitted values were plotted with *u* as the *x*-axis and *v* as the *y*-axis, which resulted in an ellipse for each set of 24 plotted points as shown in Figure 2.

The orientations of the major axes of the ellipses are similar for all four buoys with the eccentricity larger for buoys B2 and A than for buoys B1 and D2. The mean wind vector for buoy B1 is to the north-west, while that for buoy D2 is practically zero. The mean wind vector for the other two buoys is to the south-east, but the magnitude of the vector for buoy A is larger than that for buoy B2. There appears to be a systematic variation in the mean wind direction, magnitude, and the eccentricity of the wind ellipse on a roughly north-east to south-west line.

Discussion. During the period of this study most of the area covered by the JASIN study was dominated by an intense high-pressure system. However, several low-pressure systems passed through areas close to the JASIN area and had some effects on the weather within it. Wind speeds were low and a flat pressure gradient existed over the JASIN area for most of the time during the study.

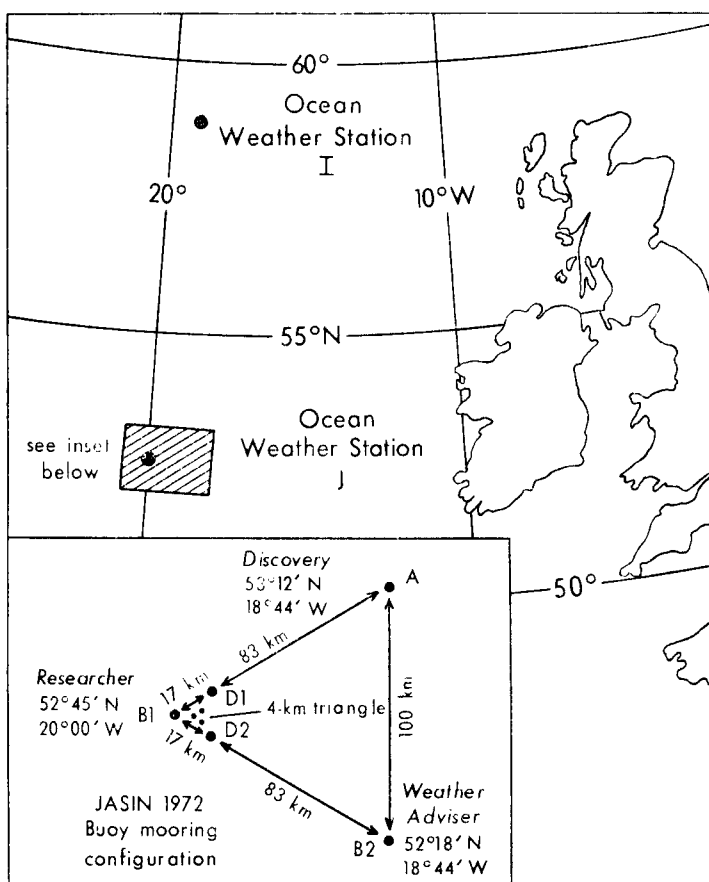


FIGURE 1—THE RELATIVE POSITIONS OF THE METEOROLOGICAL BUOYS AND PARTICIPATING SHIPS DURING JASIN 1972

Under these circumstances one would expect that the wind would vary considerably over the area in speed and direction at any given time. However, it was quite a surprise to the authors to find that the mean diurnal variation in speed and direction, when averaged over an almost two-week period, could vary so much over such short distances.

Acknowledgements. We wish to thank Professor Henry Charnock, Director of the United Kingdom Institute of Oceanographic Sciences, for inviting us to participate in JASIN 1972, and Dr Raymond T. Pollard, Co-ordinator for JASIN 1972, for assistance and encouragement in many ways.

This research was supported by the Global Atmospheric Research programme of the National Science Foundation under Grant GA 28004 and by the North Atlantic Treaty Organization under Grant #3 (SA-6-5-02(3) 39 TK).

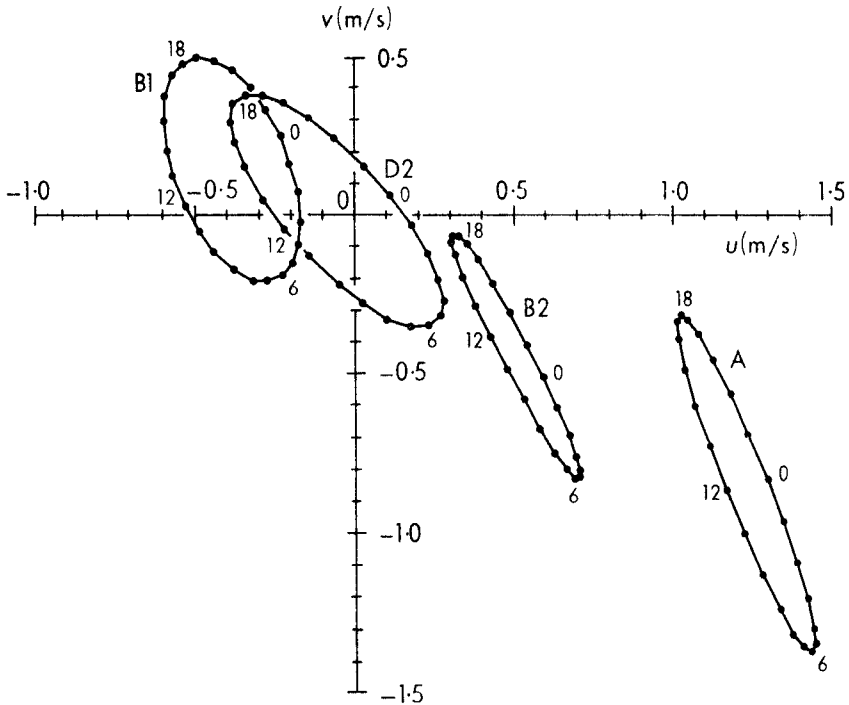


FIGURE 2—ELLIPSES CONSTRUCTED FROM THE MEAN HOURLY WIND VECTORS AS MEASURED FROM FOUR METEOROLOGICAL BUOYS DURING A 12·7-DAY PERIOD Times are shown in GMT.

REFERENCES

1. BURT, WAYNE V., ENFIELD, D. B., SMITH, R. L. and CREW, H.; The surface wind over an upwelling area near Pisco, Peru. *Boundary Layer Meteorology*, Dordrecht, 3, 1973, pp. 385-391.
2. BURT, WAYNE V., CREW, H., PLUTCHAK, N. and DUMON, J.; Diurnal variations of winds over an upwelling area off Oregon. In the press — to be published in the Brocks Memorial Edition of *Boundary Layer Meteorology*.

REVIEWS

Understanding our atmospheric environment, by Morris Neiburger, James G. Edinger and William D. Bonner. 260 mm × 175 mm, pp. xi + 293, illus., W. H. Freeman and Company Limited, 58 Kings Road, Reading, England RG1 3AA, 1973. Price: £4·70.

Weather is and always has been a topic of vital interest to man and in this present era, when there is increasing interest in our environment it is more necessary than ever to keep the non-specialist informed.

This American book is intended for non-meteorologists, for students majoring in subjects other than a physical science, and has been written as basic instruction for a course covering about one university term. Naturally, as

the authors point out, meteorology is too extensive a subject to permit all aspects to be well covered in a book of such limited scope but nevertheless they claim, justifiably in my opinion, to touch on most aspects and the book should enable the students to reach a better understanding of atmospheric phenomena and the processes which operate in the atmosphere and result in what is usually referred to as 'the weather'.

The first chapter entitled 'The drama of the weather' sets the scene and is followed by chapters covering the composition of the atmosphere, the radiation aspects and the gas laws, involving heat and temperature changes. Subsequent chapters discuss small-scale motions, large-scale motions and the general circulation, introducing topics usually covered by the term dynamic meteorology. Condensation and precipitation processes are then explained before dealing with the role of convection and the convective phenomena, thunderstorms and tornadoes.

A short chapter on air masses is followed by adequate chapters on fronts and cyclones and weather systems in the tropics.

Some space is devoted to weather forecasting and in this chapter as well as a description of some methods of weather prediction, the slightly controversial questions of predictability and accuracy of weather forecasts are also considered: examples are shown of forecasts produced by using modern electronic computers.

The final two chapters deal with air pollution and man's influence on the atmosphere, the concluding sections covering the effects of man's activities in the atmosphere — particularly in cities, and intentional weather modification experiments are discussed. Each chapter finishes with a list of questions designed to enable students to check on their understanding of the text.

This book started as a set of mimeographed notes, progressing to a preliminary edition which was then class-tested and critically examined by a large number of teaching professors in the U.S.A. This edition has undoubtedly been improved by the incorporation of suggestions arising from that exercise, and it now appears as a well-produced and well-illustrated book which fulfils in my opinion the hopes of the authors.

G. R. R. BENWELL

Principles of environmental physics, by J. L. Monteith. 215 mm × 135 mm, pp. xiv + 241, *illus.*, Edward Arnold Ltd, Woodlands Park, Maidenhead, Berkshire, 1973. Price: £6 (Paperback £3).

Progress in biology during the first half of the present century, although considerable, was to a certain extent handicapped by the absence of adequate inclusion of the relevant details from a sister-science, namely physics. Recognition of this defect has led to the institution of professorships at certain universities, and the Chair of Environmental Physics at the School of Agriculture, Sutton Bonington, University of Nottingham, is a case in point.

The occasion of the publication of a textbook in the Contemporary Biology series, by the present holder of that post, is therefore greatly to be welcomed. The author is under no illusion as to the difficulties of his task, as is shown by his pertinent quotation from Lucretius 'The main obstacles are the inadequacy of our language and the novelty of my subject'.

To overcome the language obstacle it is essential for the biologist to adopt the presentation techniques of the mathematician and mathematical physicist, no mean task when he probably abandoned the elements of both disciplines about the age of 16 in order to concentrate on a biological science. He must now prepare himself to be able to express his ideas and concepts in the form of equations, using a system of notation which may at first be foreign to him. To emphasize this the opening pages of this book contain a list of nearly 140 symbols used in the succeeding chapters — a new language indeed to someone whose previous training precluded such aids to scientific expression.

After outlining the scope of the volume, the author deals concisely and clearly with the basic physics of the gas and radiation laws. Radiation is then dealt with in greater detail, considering the analysis and interpretation of the radiation present in the environment and its modification within the domain of a plant, followed by a discussion of the all-important radiation balance. The next meteorological factor to be dealt with is wind, involving explanations of the momentum transfer in the boundary layers, the drag effect and the incidence of turbulence. This leads on to a treatment of the heat-exchange processes and the thermal balance including latent heat. Finally the book provides an introduction to the composite problems of the micrometeorology of crops, and a series of useful tables. A helpful bibliography of some 200 items is included but it is a pity that the World Meteorological Organization *Technical Note* No. 119 'The application of micro-meteorology to agricultural problems' was apparently published too late for inclusion.

Professor Monteith has dealt with a difficult and very complicated subject with admirable skill. The result is a book which the uninitiated may find difficult to digest without extensive mental effort, but the biological research student must master this approach to the solution of his problems if he is to reach real understanding of the sciences of the biosphere. The printing is of a high standard and the diagrams are excellently designed and reproduced.

L. P. SMITH

Britain's weather (its workings, lore and forecasting), by David Bowen. 220 mm × 145 mm, pp. 310, *illus.*, David and Charles (Holdings) Ltd, South Devon House, Newton Abbot, Devon, 1973. Price: £3.25.

This book is aimed very much at the meteorological layman, and attempts to cover in descriptive terms the various aspects of the weather which have an impact on man's activities. Early chapters on the basic techniques of meteorological observation are followed by sections on Weather Charts and Forecasts. Here the information is somewhat out-of-date, since very little emphasis is placed on the use of computers in the forecasting field.

General aspects of British Climate, Weather Lore and Weather Cycles are dealt with in a descriptive fashion and then in the chapter on 'Weather and Warfare', the author recounts the ways in which the weather has played a part in various military engagements from Crecy to D-Day. Mr Bowen presents two 'forecasts' which the Emperor Napoleon I would have found useful in the week leading up to Waterloo.

The section on 'Weather Control' begins with an account of 'fog sweeping', which leads into a description of the use of mesh screens at Gibraltar for the collection of water from cloud droplets. Here Mr Bowen's knowledge of the literature is shown to be less than adequate, since he attributes the initiative in this matter to E. A. J. Canessa, who first experimented there in 1968; no reference is made to G. W. Hurst's work at Gibraltar, results of which were published in 1959.

The book continues with a section on the effects of climate on man's physical (and mental) well-being and concludes with accounts of work performed by amateur meteorologists in recent years.

A general criticism of the book is that the author seems to relish recounting organizational detail when it is superfluous to his main theme, and the book would remain less obviously out-of-date if this detail were omitted. Examples of this are his stressing of the separate roles of the national and regional forecasts presented immediately before main BBC news bulletins, and his accounts of the Meteorological Office organizational structure.

To summarize, this book might be of interest to the meteorological novice, but its rather old-fashioned layout hardly makes it a bargain at £3.25 when there are other, cheaper, introductory texts on the market.

J. S. HOPKINS

The effect of thermometer screen design on the observed temperature, by W. R. Sparks. 270 mm × 210 mm, pp. 106, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1972.

The study and practice of meteorology on the world scale requires a uniform, or at least compatible, system of instrumental observations. The World Meteorological Organization (WMO) stresses this in its *Guide to meteorological instruments and observations*. Its technical notes and reports, written by specialists in particular problems, include advice and recommendations about such important matters as design, exposure and management, and assessments of desirable standards of accuracy. The present report is a valuable survey of the differing practices and the inconsistencies which still beset the apparently simple matter of measuring air temperature in the open.

Literature on thermometer screens goes back well over a hundred years. It was recognized at an early stage that to measure air temperature the thermometer must be screened from direct radiation. It was not always appreciated that the screen itself might then affect the reading. Mr Sparks discusses such effects, including the large thermal capacity of the screen which can have a very marked effect on the more transitory changes in temperature. Thus the smaller Bilham screen shows a higher maximum and a lower minimum than an adjacent similarly constructed but larger Stevenson screen. In this connection the accuracy of ± 0.5 degC in maximum and minimum temperatures set by WMO may need revising; so, too, may the 0.1-degC accuracy in 'synoptic' temperatures when an interval of 10 minutes is allowed. It is often supposed that provided different stations have identical screens at identical heights over identical ground, their temperatures will then be strictly comparable. However, a naturally ventilated screen is still affected by the local conditions of radiation and wind speed and direction.

The report is concerned only with 'dry-bulb' temperatures. The varying rate of air movement inside a naturally ventilated screen and the consequent effect on the 'wet-bulb' temperature can be an even more serious problem. Only an instrument with double radiation shields and adequate forced ventilation, properly designed for use in the open, avoids such errors. Not all Assman psychrometers are free from radiation and ventilation errors.

Mr Sparks describes numerous comparisons of various types of louvered screen. Several are of doubtful value, as the observations have not been taken at the same height, so the results do little more than confirm the existence of lapses and inversions. In this regard the WMO *Technical Regulation* permitting temperature observations between 1.25 and 2.00 m above the ground is not consistent with a required accuracy of 0.1 degC.

Under 'Novel screens' the writer describes various attempts to secure improved protection against radiation. Thus, some tropical countries erect a separate large roof of thatch or corrugated iron, the edges sometimes coming down to the level of the screen. It seems possible that air heated by contact with the roof may then enter the screen itself.

The author has had the difficult task of drawing conclusions from a mass of published information, from which even his abbreviated list extends to 90 references. He quite rightly draws attention to inconsistencies between officially recommended accuracy requirements for air temperature and the fact that we are measuring a fluctuating quantity and using an installation which has variable lag and susceptibility to radiation and wind. It is not obvious that comparisons against the CIMO-V Reference Psychrometer now being developed will lead to any better practical interpretation of screen readings. In reminding us again about the limitations of the every-day screen, Mr Sparks has made us think more carefully about what we are really trying to measure and how to do it. A cautionary tale.

Colleagues who need to use a bilingual dictionary may have difficulty with oversights in proof-reading such as Hydrometry (for Hygrometry), radio (ratio), ture (true), corregated (corrugated), and 'rigid (?) temperature fluctuations'.

S. G. CRAWFORD

Survey of instruments for micrometeorology (International Biological Programme Handbook No. 22), compiled by J. L. Monteith. 210 mm × 150 mm, pp. xii + 263, *illus.*, Blackwell Scientific Publications, Osney Mead, Oxford OX2 0EL, 1972. Price: £3.

The material for this book has largely been obtained from questionnaires returned from 21 countries by manufacturers of instruments suitable for micrometeorological studies. A separate chapter is allocated to each of the following classes of instruments: thermometers and psychrometers, hygrometers and infra-red analysers, solarimeters and pyrheliometers, net radiometers, heat flow meters, anemometers, water content meters, water vapour flux meters, recorders and integrators. Each chapter has a brief introduction in which the merits and demerits of the various types of sensors are given.

A feature of this book is that the information on sensors is laid out in a standard format with one page for each instrument. This format includes space for a picture followed by itemized information such as type of instrument and name of the maker, specification, principle of operation, size, form and display of the output, sensitivity, etc. and an approximate price in 1971. A particularly interesting item is under the title 'users' in which names and addresses of institutions and people using an instrument are given thus enabling others to obtain first-hand knowledge about it. All the information given is as supplied by the manufacturers and naturally the editor is not responsible for its accuracy. Some of the instruments are different versions of the same device made by different makers in different countries. The chapters on recorders and integrators only include instruments which are suitable for field use and therefore independent of mains voltages. The book concludes with references to relevant publications for the period 1960-70.

The promoters of this book have done their part well but this cannot be said of all those supplying information, since many did not fully complete the questionnaires and in other cases the information had to be extracted from advertising literature. This results in blank spaces on many pages especially if the picture is lacking as it is in nearly half of the cases. This is an unusual book — possibly the first of its kind. Its layout makes for easy and quick reference and anyone working with this type of instrument will find the book extremely useful and time-saving. The editor hopes to bring out additional information either in the form of a supplement or as a new edition in which, it is to be hoped, the manufacturers will be more diligent in supplying information.

H. E. PAINTER

NOTES AND NEWS

The European Centre for Medium-range Weather Forecasts

On 11 October 1973 there was signed in Brussels the Convention establishing the European Centre for Medium-range Weather Forecasts. Fifteen countries signed, and others may do so later. The project for the Centre was developed over some three years as the biggest considered by the 19-nation COST group (European Co-operation in the field of Scientific and Technical Research). The Centre will have its permanent home in a new building to be erected at Shinfield Park, near Reading, after being housed meanwhile in Bracknell. Its main task is to develop computer methods of forecasting for periods of 4-10 days, to prepare such forecasts operationally, and to distribute them to the meteorological services of member States.

The Centre will be financed by the participating European States. It is expected to need an international staff of about 120 and a computer much larger in capacity than any so far employed in meteorology. A Council composed of representatives of the member States will govern the Centre through its Director. Because of the economic value foreseen for the Centre's products it has been recognized that no time should be lost, so until the Convention comes into force (depending on its ratification by States) an Interim Committee has been set up by the signatory States to get things moving. The Committee held its first meeting in Brussels on 26 October 1973.

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NOTICES

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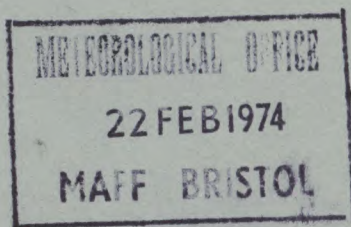
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THE DISTRIBUTION AND FREQUENCY OF HIGH CUMULONIMBUS TOPS NEAR SINGAPORE AS MEASURED BY 10-CENTIMETRE RADAR (PART I)

By F. F. HILL and R. P. W. LEWIS

(Meteorological Research Unit, Royal Radar Establishment, Malvern and
Meteorological Office, Bracknell)

Summary. Radar measurements of storms near Singapore, made during 1969 and 1970, are discussed and analysed. Especial attention is given to tops above about 50 000 ft because of their importance to supersonic transport aircraft. A marked preference for development of giant cumulonimbus in certain favoured areas is described, as also are diurnal and seasonal variations of some importance.

Introduction. *The Singapore radar project.* Owing to the absence of quantitative information on the distribution, size, and frequency of storms in equatorial regions and the need of such data for planning the operation of Concorde and other supersonic transport aircraft, radar observations were made and recorded systematically at Singapore from mid 1968 to early 1971 with a Plessey 43S 10-cm radar which had just been installed near the RAF airfield at Changi. It was originally hoped that useful data would be collected over a period of three years but mechanical and other technical problems proved difficult to surmount and it was not until August 1969 that a high level of instrumental performance and general reliability was established. Consequently the data that have been studied most carefully are those collected between September 1969 and December 1970 although earlier results have been reviewed in a more qualitative manner.

The collection of data was spread over a series of shifts, the roster being drawn up at the beginning of each month quite independently of the meteorological situation. The night shifts were restricted to six per month and similarly the basic programme only called for six morning and six evening shifts, but it was found advantageous to increase the size of the sample by working supplementary shifts whenever possible. Hence although the night sample is about 15–20 per cent of possible per month, the day sample (from 0700 to 2200 local time*) is up to twice as large (see Table I). Unfortunately it became necessary for one of the observers to be transferred from this project to synoptic duties in October 1970, so that the sample size is reduced from then on.

* All times quoted in this paper are local station time, which was $7\frac{1}{2}$ hours ahead of GMT.

TABLE I—NUMBER OF ECHO-TOP CHECKS MADE EACH HOUR

		Hour of day (local time)																							
		00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1969	Sept.	12	12	12	12	12	12	12	23	24	22	22	22	23	30	29	21	19	18	18	20	24	24	18	12
	Oct.	12	12	12	12	12	12	13	18	27	29	30	30	31	33	30	27	20	16	16	24	24	18	12	12
	Nov.	10	10	10	10	10	10	10	20	22	21	18	15	18	27	25	20	20	18	16	18	18	14	10	10
	Dec.	12	12	12	12	12	12	12	15	17	19	19	18	17	27	27	21	20	17	16	22	22	17	12	12
1970	Jan.	10	10	10	10	10	10	14	22	22	17	17	16	18	24	23	25	25	20	20	24	24	17	10	10
	Feb.	8	8	8	8	8	8	10	16	16	14	16	14	17	22	21	20	18	14	14	16	16	12	8	8
	Mar.	10	10	10	10	10	10	12	20	20	20	20	20	20	21	22	20	18	16	16	22	22	16	10	10
	Apr.	10	10	10	10	10	10	12	15	14	17	20	20	20	21	23	20	17	16	16	20	20	15	10	10
	May	12	12	12	12	12	12	12	19	19	18	18	18	21	22	22	22	20	18	19	26	26	19	12	12
	June	12	12	12	12	12	12	16	22	20	21	22	22	21	24	23	22	21	20	20	24	24	18	12	12
	July	12	12	12	12	12	12	13	20	20	20	20	19	19	21	22	22	22	22	22	24	24	18	12	12
	Aug.	10	10	10	10	10	10	10	16	18	18	18	18	17	24	24	24	23	20	20	22	22	16	10	10
	Sept.	12	12	12	12	12	12	13	24	22	22	22	22	22	25	25	24	23	22	23	22	22	17	12	12
	Oct.	12	12	12	12	12	12	12	18	18	18	16	14	14	14	15	16	16	16	16	18	18	15	12	12
	Nov.	12	12	12	12	12	12	12	12	11	12	12	12	12	14	14	12	12	12	12	16	16	13	12	12
	Dec.	10	10	10	10	10	10	10	10	10	10	10	10	10	14	18	17	13	10	10	11	16	10	10	10

The work-programme consisted of :

- (a) at each hour during the main shifts, taking a sequence of photographs of the 240-nautical mile (n. mile) range display at 1° elevation-steps from 0° to 11° ;
- (b) during all shifts, making measurements every half hour of all high tops within 120 n. mile and the maximum intensities of these echoes;
- (c) every 15 minutes or so, taking photographs at two or three different elevations to show the main features of the distribution and development of the echo;
- (d) comparing the radar evidence with synoptic observations and with any aircraft reports.

The photographs taken in (a) were required for plotting on a grid for subsequent analysis by computer so that information could be obtained on the distribution of weather-echoes at low and middle levels; this will be the subject of a separate study. Consequently the main concern here is only with the high tops measured in (b), obtained directly from a plan position indicator (PPI) display, using swept-gain normalized at 108 n. mile or 200 km. ('Swept-gain' is a device incorporated in the radar which produces an automatic inverse-square-law reduction of intensity for all echoes received from within 108 n. mile; this means that, provided they fill the radar beam, all targets of the same reflectivity should produce signals of the same intensity on the screen for all distances up to 108 n. mile.) The method of finding and measuring these high tops is fundamental to much of what follows, so it will be described in detail. Each 10-n. mile range interval was examined in turn, from the outermost inwards, for any echoes appearing at a critical elevation angle which was different for each range interval and chosen so that all tops above 40 000 ft were certain to be recorded. (These critical angles and their implied ranges of height are illustrated in Figure 1; in fact, a large proportion of the tops above 35 000 ft were also measured.) Each echo was followed upwards by increasing the angle of elevation of the aerial until it just disappeared; the height of the top of the echo was then obtained from its slant range and maximum angle of elevation by use of tables which incorporated allowances for the curvature of the earth and the variation with height of the refractive index in a standard tropical atmosphere.

At the time of writing, the echo-top data are also being put into machinable form so that a more thorough analysis of the records, including comparisons with computed heights made using the Singapore upper-air soundings (cf. Roach and James¹) will then be possible; in the meanwhile, however, the authors believe that the necessarily limited results of the preliminary analysis described in this paper will nevertheless be of interest.

Accuracy of the measurements. It has become accepted over the last decade that the height of cumulonimbus (Cb) tops in tropical areas may exceed 50 000 ft, a figure which previously might have been thought improbably large. Although Concorde may cruise well above active weather in middle and high latitudes, its expected cruising level of about 55 000 ft may bring it dangerously near such giant Cb in the tropics; it is important therefore that sources of error in the heights measured in this radar project should be carefully considered, and that these heights should if possible be shown to be consistent with measurements made directly from aircraft.

The most serious errors in the measurements of echo-tops are likely to be due to the return of the outer parts of the main lobe or the side-lobes from intensely reflective parts of the storm below the actual top. Donaldson² has calculated probable errors in echo-top measurements for model storms of different intensities, shapes and vertical profiles for two types of radar, one of which had characteristics similar to those of the 43S. It appears from his work that maximum reflectivities need to be of order $10^6 \text{mm}^6 \text{m}^{-3}$ before radar measurements are consistently in excess of the true tops. Fortunately, the highest reflectivities observed at Changi were only about $10^5 \text{mm}^6 \text{m}^{-3}$ and the storms there were not so intense in their upper parts as the models in Donaldson's paper that gave the largest errors; the models that are more typical of the Singapore storms give radar tops to within 5000 ft of the true top out to 100 n. mile and in some storms the radar top can be below the true top.

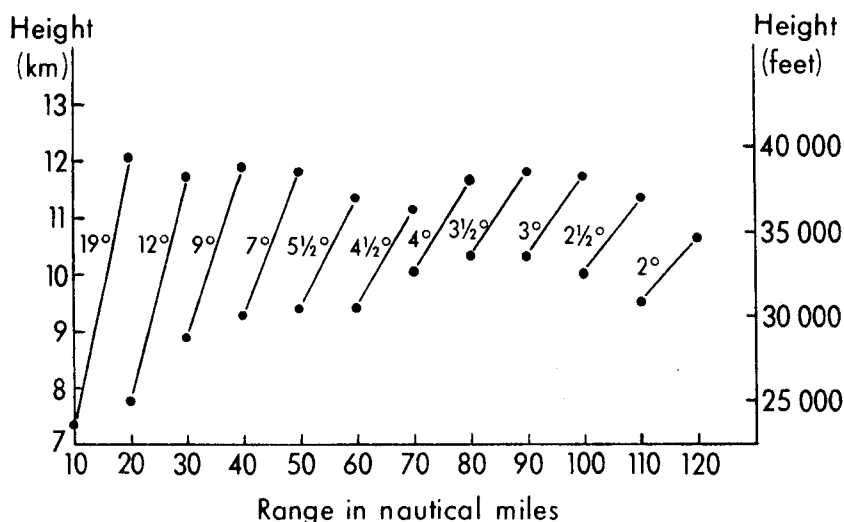


FIGURE 1—ELEVATION AND RANGE CRITERIA USED FOR ROUTINE MEASUREMENTS OF ECHO-TOPS DURING PERIODS OF WIDESPREAD ACTIVITY

The elevation angles of echo-tops were measured to the nearest $\frac{1}{4}^\circ$; neither the specification of the elevation control nor the clarity of the elevation dial permitted greater accuracy to be attempted and human errors and bias could influence the data. Such errors are most likely to cause doubt in the measurements of the more distant echoes; at 120 n. mile an error of $\frac{1}{4}^\circ$ is equivalent to 3000 ft. One might expect the number of echo-tops above a certain height to have a greater density at long range since errors due to side-lobe effects and beam-width will be positive. The following table gives the numbers of echo-tops above 50 000 ft recorded within stated ranges between September 1969 and December 1970 (inclusive).

TABLE II—NUMBERS OF ECHO-TOPS ABOVE 50 000 FEET RECORDED BETWEEN SEPTEMBER 1969 AND DECEMBER 1970

Range <i>n. mile</i>	Number of tops observed	Number of tops expected on assumption of even density
31-60	207	200
61-90	381	332
91-120	410	466

This table yields a value of χ^2 of 14.2 with two degrees of freedom, which is significant at less than the 0.1 per cent level. The distribution of recorded tops is therefore almost certainly not random, but the cause of the non-randomness cannot be accurately diagnosed; the distribution of land and sea round Singapore is far from homogeneous and this influences the distribution of areas of strong convection. It is also possible that the relative deficiency of tops in the outer annulus may be due to the failure of distant clouds to fill the beam completely, or to an excessively cautious measurement of the distant echoes; it is interesting in this connection to note that Lee and McPherson³ comment on the smallness of the diameter of Malaysian storms compared with those of similar height over Oklahoma.

During October 1968, flights using two aircraft were made over southern Malaya on 21 afternoons (Lee and McPherson³); one aircraft could fly above the tops, which helped to establish their heights more accurately, and both aircraft could be directed toward storm areas by guidance from the Changi radar operator. During this project there was a small number of occasions when aircraft and radar measurements of tops could be compared and these demonstrated good agreement as may be seen from the following table.

TABLE III—COMPARISON OF HEIGHTS OF CUMULONIMBUS TOPS AS MEASURED FROM AIRCRAFT AND BY RADAR

Date 1968	Aircraft height <i>km</i>	Radar height <i>km</i>
2 Oct.	16	15
2 Oct.	16	15-16
2 Oct.	14	14
3 Oct.	15 (anvil)	13
3 Oct.	16	16-13 (decaying)
16 Oct.	15	14
16 Oct.	17	16

The 'aircraft heights' were those measured by altimeter and subsequently corrected for the *D*-value* difference between ICAN heights and those appropriate to the actual upper-air structure over Singapore on the day in question; they were originally given in thousands of feet. Radar performance was very variable at this time owing to a fault in the equipment but on the days in question it appeared to be satisfactory. It is clear that the radar heights tend to be lower by about 1 km than the aircraft heights.

* The *D*-value is the difference, *D*, between the actual height above mean sea level of a particular pressure surface and the pressure altitude (the height of the same surface in the International Civil Aviation Organization Standard Atmosphere).

Indirect support for the accuracy of the radar measurements is given in the paper by Roach and James¹ in which it is shown that calculations of the maximum parcel-top height from the Singapore upper-air soundings agreed well with the observed radar tops during the period September–November 1969.

Overall, therefore, we may say that the radar height estimates are probably fairly realistic and should be correct to within at most 6000 ft (2 km) of the true top and often within 3000 ft. Larger errors are likely to be more numerous beyond about 80 n. mile but the heights are not necessarily exaggerated — indeed the reverse may well be more likely. Because the radar was insensitive to very small droplets the agreement between true and measured tops is closest during the periods of growth and maximum development, and hence the figures to be reviewed refer to the tops of Cb at their most vigorous stages. The true frequencies of Cb tops at a given level, including those that are decaying, are thus likely to exceed the values given.

Overall frequency of high tops. A general idea of the distribution of high tops may be obtained from Tables IV–VIII. Table IV shows the variation throughout the day of the mean height of the highest echo-top recorded at the regular half-hourly checks for each of the 16 months from September 1969 to December 1970. (The mean heights for 15 and 45 minutes past each hour are further averaged to give one mean height for the complete hour of 60 minutes.)

It is necessary to state here that before January 1970 the entry 'Nil Sig' was made if there were no echoes satisfying the criteria for measuring tops. These criteria were originally designed to ensure that all tops over 30 000 ft were recorded, but after the correction of a long-standing instrumental fault in August 1969 it was found necessary to raise the limit to 40 000 ft during periods of widespread activity. (See also above and Figure 1.) The staggered form of these criteria result in about 60 per cent of the tops above 35 000 ft also being recorded and these minima were 'stretched' whenever possible so that the losses at the upper distances of each range-step were reduced. It is clear from the records that 'Nil Sig' was not entered if any tops were higher than about 9 km; further, it is likely that there were almost always Cu present somewhere within 120 n. mile of Singapore at heights of at least 3 km which would not necessarily be recorded on the radar screen since the base of the beam rose to nearly 3 km at a range of 120 n. mile. Consequently, for the calculation of the mean highest top, a nominal substitution of 6 km was made for an entry of 'Nil Sig', and 3 km for one of 'Nil Echo'. The month mainly affected by these substitutions was December 1969; after the beginning of January 1970 the highest top was recorded irrespective of any lower limit.

It was also unfortunate that a reduction in sample size became necessary from October 1970 onwards because the previous October had been very active. It is known from other radars and weather reports that several days of substantial activity were missed on this account so that the records for October 1970 may not be as typical of a transitional month as they should; by contrast in October 1969 a run of storms in the second half of the month was sampled more completely than usual.

The area scanned by the radar to which the present results apply is about 45 000 (n. mile)². It contains an interesting configuration of land and sea

TABLE IV—MEAN HEIGHT OF HIGHEST TOP AT EACH CHECK

		Hour of day (local time)																							Overall	
		00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22		23
		kilometres																								
1969																										
	Sept.	7.3	7.9	7.8	8.0	11.7	12.9	12.9	11.3	11.2	10.6	10.3	11.0	12.4	13.3	14.6	15.5	14.3	12.9	12.0	11.5	8.7	8.5	7.7	7.9	10.9
	Oct.	13.4	13.7	13.5	13.1	13.9	14.2	13.2	14.1	13.9	14.8	13.0	13.3	14.7	14.9	15.8	16.7	15.1	13.1	13.0	12.5	12.1	10.1	11.3	13.0	13.6
	Nov.	12.9	12.1	11.8	12.2	11.8	10.1	11.3	12.8	12.5	12.1	12.9	12.4	13.3	12.8	13.0	13.4	14.0	14.0	13.3	13.4	11.5	11.2	10.7	11.7	12.4
	Dec.	10.8	10.5	10.5	11.7	11.4	11.3	11.5	10.7	10.2	10.9	10.6	9.1	10.1	11.2	12.1	12.1	12.1	10.9	10.2	10.3	11.3	10.5	11.0	10.7	10.9
1970																										
	Jan.	10.1	9.3	8.4	8.3	8.0	8.0	7.4	7.9	8.3	8.1	7.7	8.2	8.3	9.2	9.3	10.1	10.2	9.2	8.4	8.5	9.2	9.1	9.4	10.2	8.8
	Feb.	5.1	5.4	6.8	6.4	6.3	5.9	5.7	4.4	4.4	4.7	4.9	4.7	6.0	7.2	6.9	7.0	7.3	7.2	6.6	5.8	5.8	5.4	6.3	5.2	5.9
	Mar.	11.3	10.8	11.5	10.4	9.5	9.8	8.8	9.1	8.8	9.2	8.8	8.7	8.4	12.2	12.1	12.8	14.3	13.0	11.0	9.0	8.5	6.8	7.6	9.8	10.1
	Apr.	11.9	12.7	11.9	12.8	13.5	13.8	12.1	11.8	11.3	10.9	11.5	12.7	13.7	14.2	14.7	15.6	15.8	13.0	11.4	11.0	12.8	12.6	12.5	12.1	12.8
	May	11.4	12.0	13.2	14.6	13.6	13.3	13.5	12.1	11.7	12.0	11.6	11.5	12.0	13.3	14.0	15.1	15.2	14.3	13.4	11.9	11.3	10.7	11.3	11.5	12.7
	June	6.6	6.5	8.0	10.3	10.2	10.3	9.7	10.6	10.7	10.1	10.4	11.2	10.7	9.7	11.2	11.4	12.0	10.6	9.6	9.7	8.8	7.3	7.8	6.5	9.6
	July	6.5	8.9	9.2	8.8	8.7	7.6	8.1	10.7	10.6	9.8	9.5	9.5	10.4	11.1	11.8	11.6	11.7	11.0	9.9	8.3	7.0	6.0	5.0	6.3	9.1
	Aug.	7.1	8.4	7.6	7.0	10.0	9.7	10.9	11.1	11.4	10.1	10.4	10.6	10.2	11.1	12.1	13.1	12.7	12.6	11.1	9.3	8.0	7.8	7.0	5.6	9.8
	Sept.	6.3	8.2	9.5	11.7	10.9	11.4	11.7	10.5	10.0	9.9	9.7	10.7	12.0	10.5	12.1	12.9	12.6	11.6	9.9	8.4	6.7	6.8	6.7	7.3	9.9
	Oct.	10.9	11.5	10.9	10.9	10.7	11.3	10.6	12.2	11.7	10.6	10.4	9.8	9.3	10.4	9.5	10.8	10.9	11.6	10.8	11.3	9.7	8.1	8.5	11.1	10.6
	Nov.	11.7	12.9	13.5	12.1	11.6	11.5	10.2	11.5	12.0	11.3	10.2	10.3	10.8	10.3	12.3	13.2	12.4	12.9	11.9	12.0	10.7	10.8	10.1	11.2	11.6
	Dec.	9.8	10.9	10.9	9.6	9.2	9.1	7.6	8.9	7.8	7.0	7.6	8.2	8.8	10.0	10.9	11.7	12.5	11.9	10.5	10.6	9.1	9.1	9.5	9.2	9.6

TABLE V—HEIGHT OF HIGHEST TOP OBSERVED IN EACH MONTH

	Hour of day (local time)																								Ex- treme
	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
	<i>kilometres</i>																								
1969																									
Sept.	16.3	16.7	15.9	14.1	18.0	18.7	18.8	18.3	17.6	17.0	16.6	16.9	16.6	17.3	19.7	20.2	18.3	17.3	16.8	18.2	19.9	21.4	16.7	16.6	21.4
Oct.	15.2	17.6	18.8	15.8	15.9	20.1	16.6	17.7	18.7	20.3	18.4	17.8	19.8	18.7	19.9	20.9	19.3	17.8	18.7	17.3	18.7	16.2	17.4	16.3	20.9
Nov.	14.7	16.4	17.5	17.5	18.7	17.1	15.9	17.1	16.5	16.1	15.6	18.5	16.9	21.0	17.1	16.3	17.4	20.6	16.3	16.7	19.0	18.5	16.9	16.5	21.0
Dec.	16.6	16.4	16.5	16.7	16.0	17.6	17.9	15.9	17.5	15.4	16.3	16.1	16.0	16.7	18.7	15.8	16.2	14.8	14.5	14.2	16.3	15.0	13.9	15.2	18.7
1970																									
Jan.	14.0	14.4	15.7	14.2	12.5	12.9	12.5	12.8	12.7	12.3	12.6	11.2	13.7	14.9	15.5	17.1	17.9	16.3	16.5	18.2	17.7	16.7	15.4	16.2	18.2
Feb.	7.5	10.3	13.4	12.3	12.8	9.7	11.0	10.1	10.5	10.4	10.3	9.3	12.3	12.5	13.6	12.3	12.3	12.9	11.0	9.4	11.6	10.4	12.6	8.1	13.6
Mar.	13.9	14.2	13.7	14.0	13.9	14.9	13.1	14.7	13.3	15.9	13.1	14.8	14.8	17.2	16.7	17.2	18.0	16.5	17.6	15.2	14.1	13.4	14.3	14.2	18.0
Apr.	14.2	14.9	14.1	15.6	17.8	16.3	15.7	15.0	15.1	14.6	15.1	15.4	16.0	18.3	19.6	18.7	19.3	17.2	17.2	19.4	17.7	18.9	15.7	16.7	19.6
May	12.9	17.2	15.5	17.3	15.4	16.3	17.3	16.8	16.0	17.3	15.0	14.5	16.0	17.6	17.4	19.3	20.3	17.9	17.2	18.5	18.0	15.5	15.4	15.2	20.3
June	11.5	12.5	15.7	16.1	17.2	16.3	14.5	16.4	15.7	13.5	14.3	15.1	13.1	15.5	16.1	16.7	16.2	14.5	14.3	14.3	11.6	12.6	12.9	12.6	16.7
July	13.9	15.6	15.3	16.5	14.9	12.9	13.1	15.0	16.5	14.5	16.1	13.3	14.0	15.9	18.3	18.3	18.4	18.0	19.7	16.4	14.2	15.2	12.8	15.2	19.7
Aug.	13.6	18.5	14.5	14.6	14.4	12.1	15.5	16.7	16.9	15.8	15.9	14.0	13.9	16.5	17.5	17.8	17.8	18.7	18.3	14.5	17.5	16.2	13.9	9.5	18.7
Sept.	12.1	13.7	13.7	14.3	13.8	15.9	15.4	15.2	15.5	14.5	13.5	16.6	14.7	14.3	17.3	18.7	19.3	17.3	15.5	17.2	11.5	15.9	11.4	11.9	19.3
Oct.	14.9	15.2	16.2	14.8	15.7	13.4	16.1	15.9	14.6	13.9	14.4	14.3	13.4	15.9	16.5	15.0	14.3	17.9	16.1	17.2	15.1	13.0	14.5	14.8	17.9
Nov.	16.5	17.6	16.8	17.0	13.7	15.0	14.0	13.9	13.9	14.5	11.7	13.3	15.5	15.8	16.8	17.1	16.1	16.0	15.9	15.7	15.5	12.6	16.3	16.9	17.6
Dec.	13.0	15.2	14.3	12.7	12.8	13.9	12.2	11.7	10.3	10.2	12.7	12.1	13.1	13.3	14.0	14.5	14.7	15.3	14.5	13.6	14.9	14.6	15.3	12.6	15.3
Ex- treme	16.6	18.5	18.8	17.5	18.7	20.1	18.8	18.3	18.7	20.3	18.4	18.5	19.8	21.0	19.9	20.9	20.3	20.6	19.7	19.4	19.9	21.4	17.4	16.9	

permitting much opportunity for a variety of developments either initiated or distorted by orographic influences. Although land forms only about 30 per cent of this area, it thus exerts some effect on a much larger proportion — perhaps 60 per cent to 80 per cent — the effect being most pronounced during the season of the south-west monsoon and the transitional periods, i.e. from April to October. The results of the present investigation may therefore give an exaggerated impression of the amount of storm activity in the equatorial zone in general, especially in oceanic areas; however, the sort of activity seen here is not likely to be worse than would be seen over Sumatra, Borneo, or several of the large islands that lie on or near the air-routes from south-east Asia to Australia.

Table VI indicates that it was rare to have more than 2 or 3 tops over 50 000 ft simultaneously except during the afternoons of September and October in 1969 and of April and May in 1970 when from 5 to 8 were observed. There were several months when, with a good sample, the numbers were small even in the afternoon. It will also be seen that although the morning samples were substantially bigger in most months than the night samples, the greatest number of tops observed at given levels was frequently less, suggesting that a significant lull occurred during the early morning. In most months quite a small sample was enough to produce highest tops of about 14 km (45 000 ft) in height at each hour. Given a complete set of measurements hour by hour throughout each month it would seem that a maximum height of about 17 km (55 000 ft) might occur at any time but there are some hours at which such an occurrence is much more frequent than at others; in consequence the mean height of highest top (Table IV) shows a large diurnal variation.

So that random fluctuations may be smoothed out to some extent while any significant seasonal variations are preserved, it is worth while combining figures for individual months from Table IV according to the main seasons apparent at Singapore. Figures 2(a) to 2(d) show mean diurnal variations of height of highest echo-top for the south-west monsoon period, the north-east monsoon period, the combined transitional periods, and for the complete set of 16 months being considered. Some significant properties of the diurnal variations are immediately obvious: the biggest diurnal range of height occurs during the south-west monsoon with a very marked depression of activity round midnight; heights are considerably greater during the transitional months when low-level winds tend to be lighter and more variable in direction than at other times of year; and activity has a more noticeable subsidiary night-time peak during the north-east monsoon than during the rest of the year.

The presence of a semi-diurnal (i.e. 12-hour) component in the variations for all seasonal groupings is also obvious. If the results for the whole 16-month period are harmonically analysed the phase of the semi-diurnal component is such that maxima occur at times (having allowed for the difference between local clock time and true local mean time) of 0330 and 1530 which are very close to the times of minima of the travelling component of the semi-diurnal pressure wave, viz. 0344 and 1544 (Chapman and Lindzen⁴). There may possibly, therefore, be a link between convective activity at Changi and atmospheric tidal action as suggested by the work of Brier and Simpson⁵; on the other hand, night-time cooling effects, both at low levels (producing

TABLE VI—GREATEST NUMBER OF TOPS AT ANY ONE CHECK OVER 15.3 km (50 000 ft)

		Hour of day (local time)																							
		00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1969	Sept.	1	2	1		3	3	2	2	2	1	1	1	2	3	4	7	3	2	1	2	3	4	2	1
	Oct.		3	1	1	2	1	1	3	4	4	2	2	4	7	8	5	4	2	2	2	1	1	1	1
	Nov.		1	2	1	2	1	1	1	1	1	1	1	2	1	5	1	2	2	1	2	1	2	3	2
	Dec.	2	1	2	1	2	2	3	1	1	1	1	1	1	1	1	1	1							
1970	Jan.		1												1	1	2	5	1	1	1	1	1	1	1
	Feb.																								
	Mar.									1					1	2	2	2	3	1					
	Apr.				1	2	1	1					1	1	6	3	5	4	2	1	2	3	1	1	1
	May		1	1	1	1	1	2	1	1	1			1	2	6	5	2	3	2	2	2	1	1	1
	June			1	1	1	1		1	1	1			1	1	1	1	1							
	July		1	1	1					1	1	1		1	2	4	3	3	2	1	1				
	Aug.	2						1	2	2	2	1			1	2	1	2	1	1	1	1			
	Sep.						1	1		1			1			1	3	2	1	3	2	1			
	Oct.			2		1		1	1					1	1	1			3	1	1				
	Nov.	1	1	2	1										1	1	1	2	2	2	1	3	1	1	1
	Dec.																			1				1	1

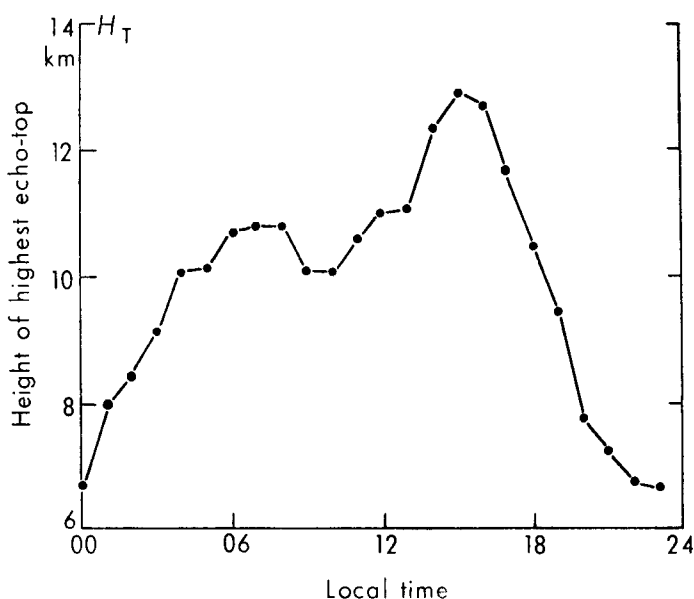


FIGURE 2(a)—DIURNAL VARIATION OF HEIGHT H_T OF HIGHEST ECHO-TOP WITHIN 120 NAUTICAL MILES OF CHANGI FOR THE SOUTH-WEST MONSOON PERIOD (SEPTEMBER 1969, JUNE 1970, JULY 1970, AUGUST 1970 AND SEPTEMBER 1970)

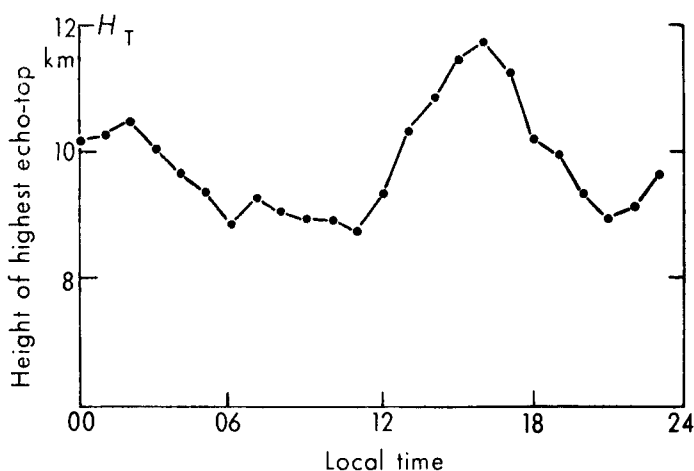


FIGURE 2(b)—DIURNAL VARIATION OF HEIGHT H_T OF HIGHEST ECHO-TOP WITHIN 120 NAUTICAL MILES OF CHANGI FOR THE NORTH-EAST MONSOON PERIOD (NOVEMBER 1969, DECEMBER 1969, JANUARY 1970, FEBRUARY 1970, MARCH 1970, NOVEMBER 1970 AND DECEMBER 1970)

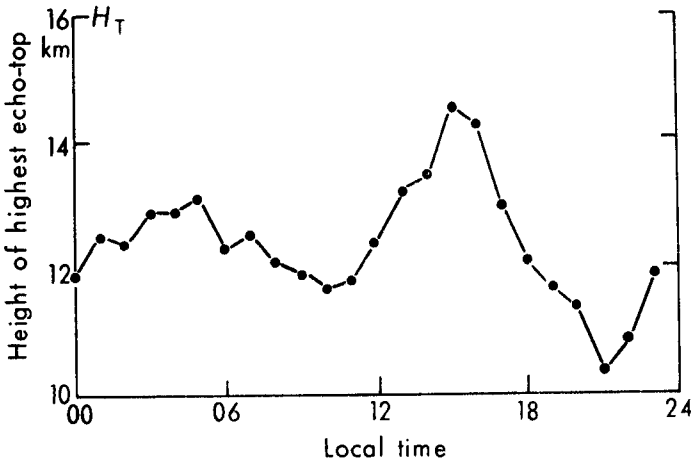


FIGURE 2(c)—DIURNAL VARIATION OF HEIGHT H_T OF HIGHEST ECHO-TOP WITHIN 120 NAUTICAL MILES OF CHANGI FOR TRANSITIONAL PERIODS (OCTOBER 1969, APRIL 1970, MAY 1970 AND OCTOBER 1970)

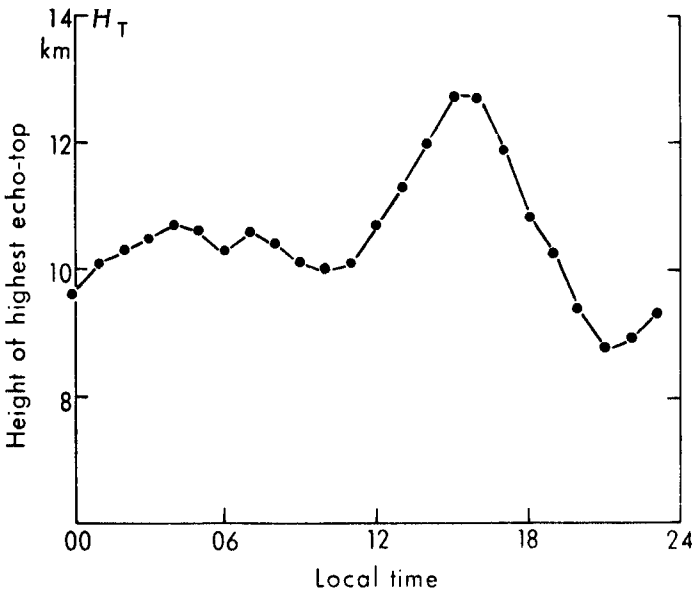


FIGURE 2(d)—DIURNAL VARIATION OF HEIGHT H_T OF HIGHEST ECHO-TOP WITHIN 120 NAUTICAL MILES OF CHANGI FOR ALL 16 MONTHS (SEPTEMBER 1969-DECEMBER 1970)

areas of convergent katabatic winds in the complex mixture of sea and mountainous land surrounding Singapore) and at high levels (leading to upper instability) may be the true, or at least a more important, cause.

It is of interest to compare the diurnal variation of height of highest echo-top with that of thunderstorm activity at Singapore which is illustrated in Figure 3; the general resemblance is obvious. We may similarly compare the run from September 1969 to December 1970 of monthly mean values of the average height of highest echo-top taken over the whole day (shown in Figure 4(a)) with the corresponding figures for thunderstorm activity (Figure 4(b)).

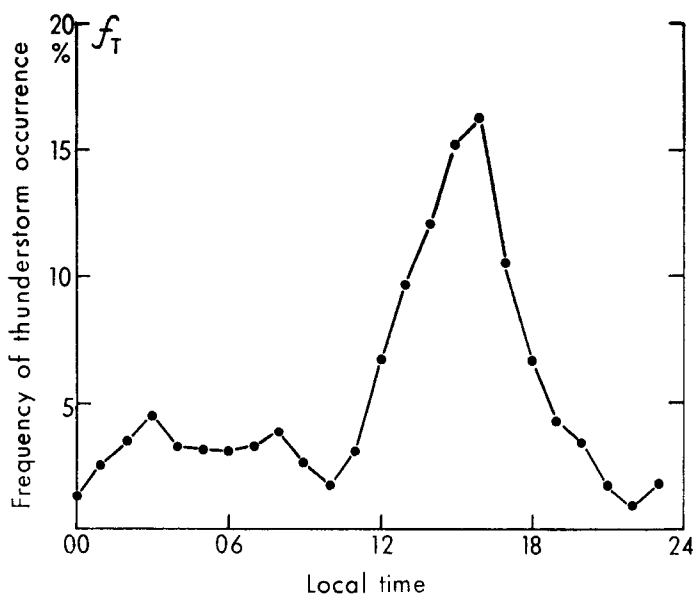


FIGURE 3—DIURNAL VARIATION OF MEAN PERCENTAGE FREQUENCY f_T OF THUNDERSTORM OCCURRENCE AT SINGAPORE, SEPTEMBER 1969–DECEMBER 1970

Spatial and diurnal distribution of the higher tops. Figures 5 to 11 show the position of the echo-tops over 50 000 ft in certain months or combinations of months plotted for three periods of the day. Because the numbers of checks in these periods were not necessarily the same they are stated on the diagrams; so also is the sample size which is given as a percentage of the total number of half-hourly observations possible in each period per month (or combination of months). The months for which plots are given were selected because good samples were available and because they conveniently illustrate the changes in distribution and density that occurred as the south-west monsoon (September 1969) was replaced by the north-east monsoon (transitional and moist from October to December, markedly drier from January to March), whereas the April and May figure (Figure 9) shows the south-west monsoon becoming re-established.

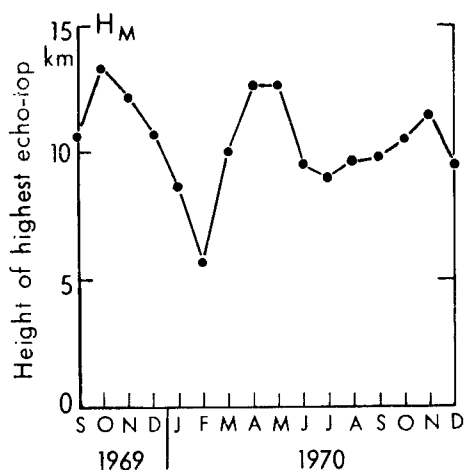


FIGURE 4(a)—MONTHLY MEAN HEIGHT H_M OF HIGHEST ECHO-TOP WITHIN 120 NAUTICAL MILES OF CHANGI, SEPTEMBER 1969–DECEMBER 1970

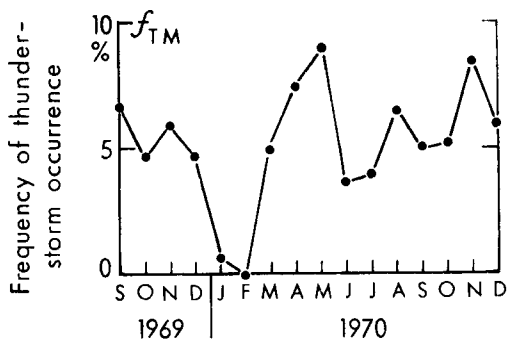


FIGURE 4(b)—MONTHLY MEAN PERCENTAGE FREQUENCY OF THUNDERSTORM OCCURRENCE AT SINGAPORE FOR SAME PERIOD AS IN FIGURE 4(a)

A marked feature of the distributions is that activity occurs mainly over the land during the afternoon and evening, and over the sea during the night and morning; even at the 40 000-ft level (see Figure 10 for April and May, 0001 to 1200 only) most of the echoes over Malaya shown as occurring in the morning formed in fact after 1100 (local time) so that the contrast between land and sea is still dominant.

Since the number of checks made between 0001 and 1200 was in all months greater than in either of the two six-hour periods 1200 to 1800 and 1800 to 2359, the diagrams also demonstrate that the frequency of tops above



PLATE I—SITE OF THE PILOT EXPERIMENT OF A METEOROLOGICAL/ENTOMOLOGICAL
STUDY AT SHINFIELD PARK, NEAR READING

See page 53.

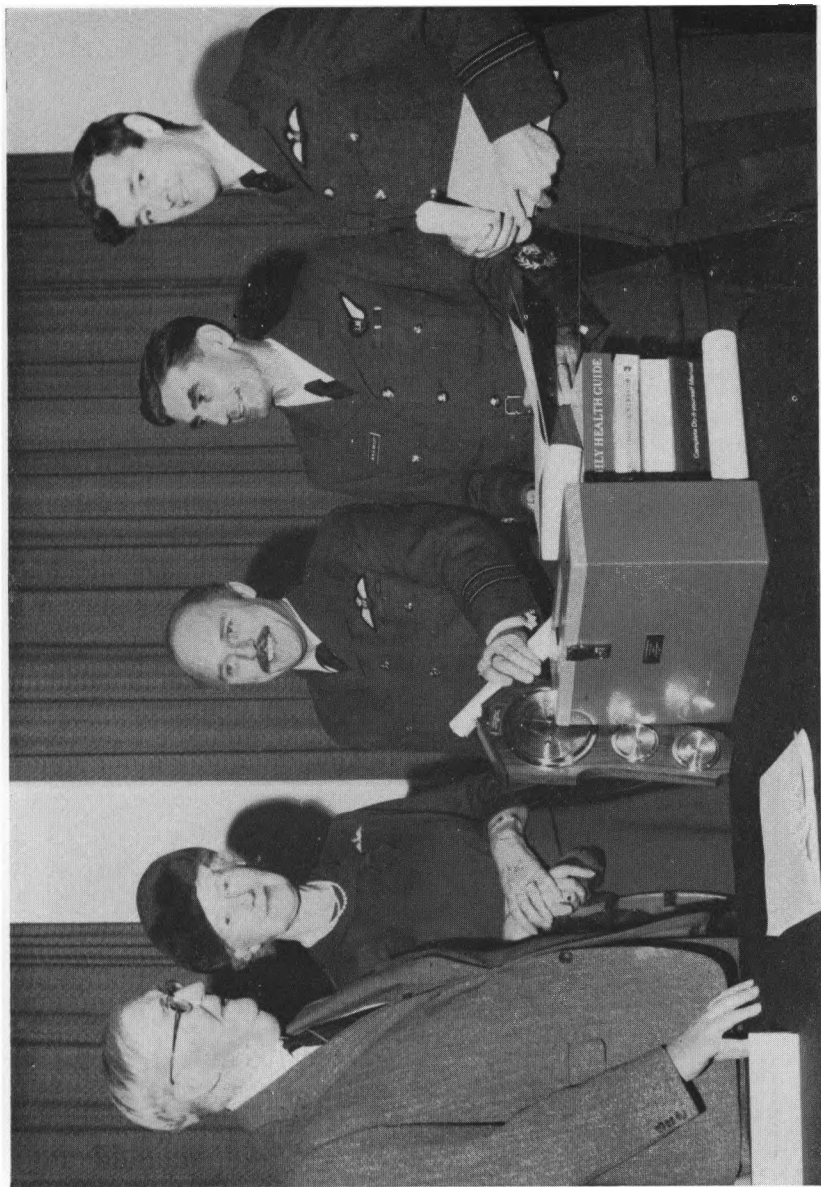


PLATE II—MAJOR AND MRS K. G. GROVES WITH SQUADRON LEADER N. LAMB,
MASTER AIR LOADMASTER M. W. BAILEY AND FLIGHT LIEUTENANT P. WALLIS

See page 55.



PLATE III—SQUADRON LEADER N. LAMB, METEOROLOGICAL RESEARCH FLIGHT,
WINNER OF THE METEOROLOGICAL OBSERVER'S AWARD

See page 56.



PLATE IV—CANBERRA AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT PHOTOGRAPHED AT JEFFERSON COUNTY AIRPORT, COLORADO, WHILST DETACHED ON PROJECT WAMFLEX

See page 56.

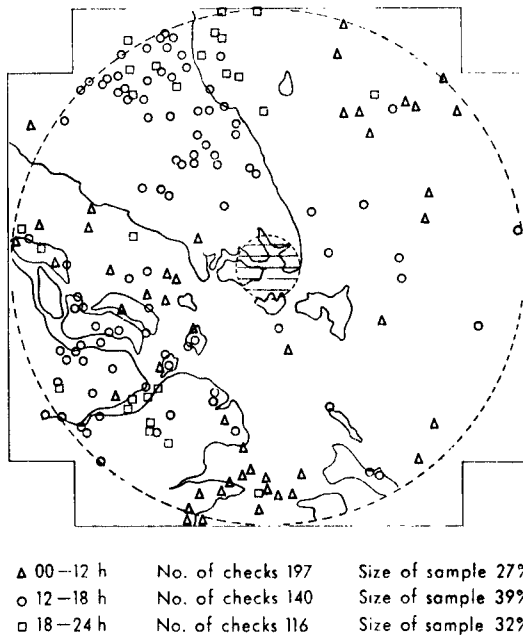


FIGURE 5—DISTRIBUTION OF ECHO-TOPS OVER 50 000 FEET IN SEPTEMBER 1969

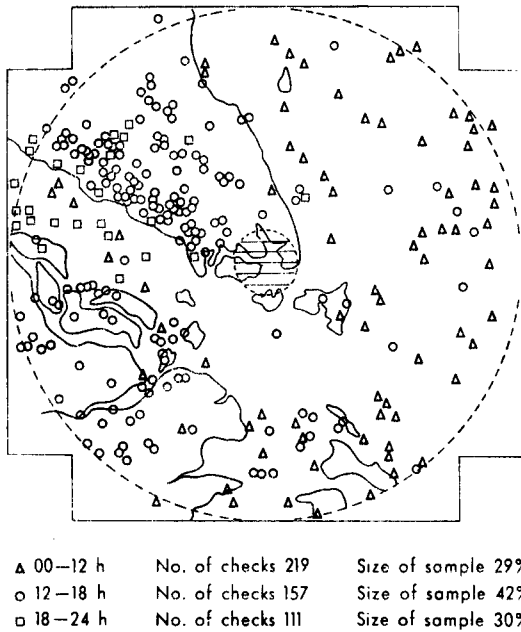
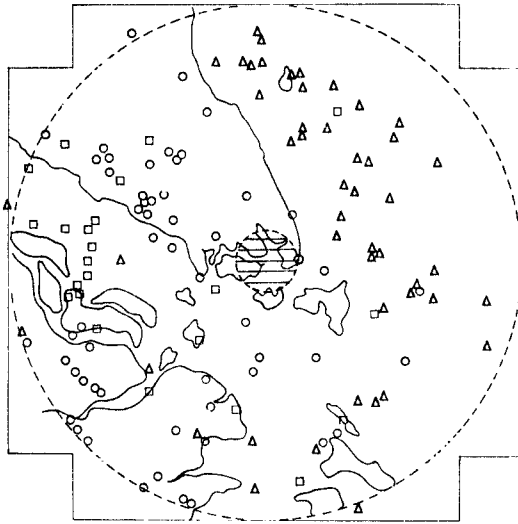
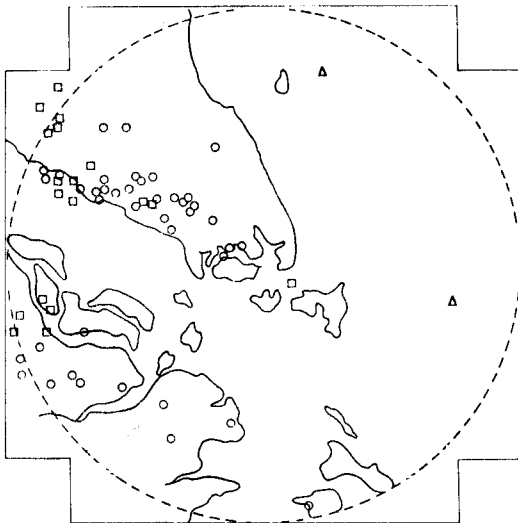


FIGURE 6—DISTRIBUTION OF ECHO-TOPS OVER 50 000 FEET IN OCTOBER 1969



△ 00—12 h	No. of checks 338	Size of sample 23%
○ 12—18 h	No. of checks 257	Size of sample 35%
□ 18—24 h	No. of checks 197	Size of sample 27%

FIGURE 7—DISTRIBUTION OF ECHO-TOPS OVER 50 000 FEET IN NOVEMBER AND DECEMBER 1969



△ 00—12 h	No. of checks 474	Size of sample 22%
○ 12—18 h	No. of checks 364	Size of sample 34%
□ 18—24 h	No. of checks 297	Size of sample 27%

FIGURE 8—DISTRIBUTION OF ECHO-TOPS OVER 50 000 FEET IN JANUARY, FEBRUARY AND MARCH 1970

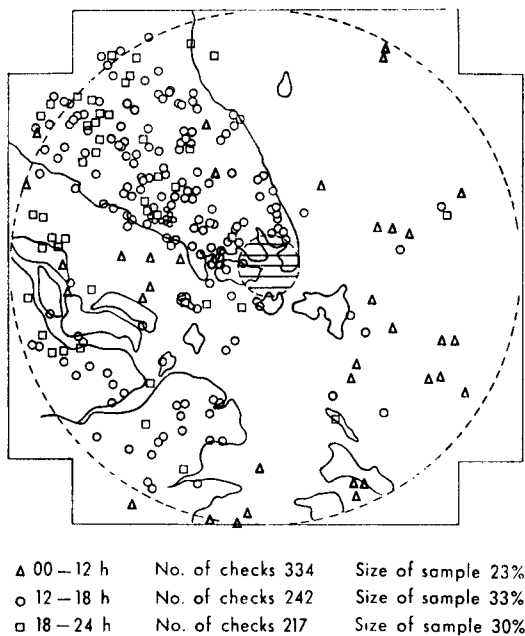


FIGURE 9—DISTRIBUTION OF ECHO-TOPS OVER 50 000 FEET IN APRIL AND MAY 1970

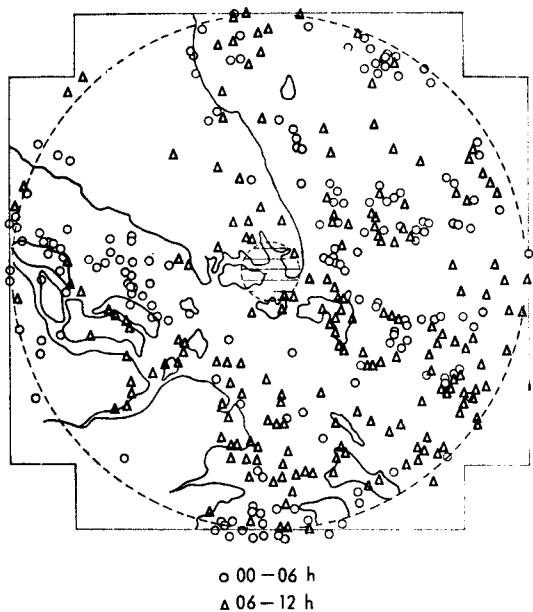


FIGURE 10—DISTRIBUTION OF ECHO-TOPS OVER 40 000 FEET IN APRIL AND MAY 1970

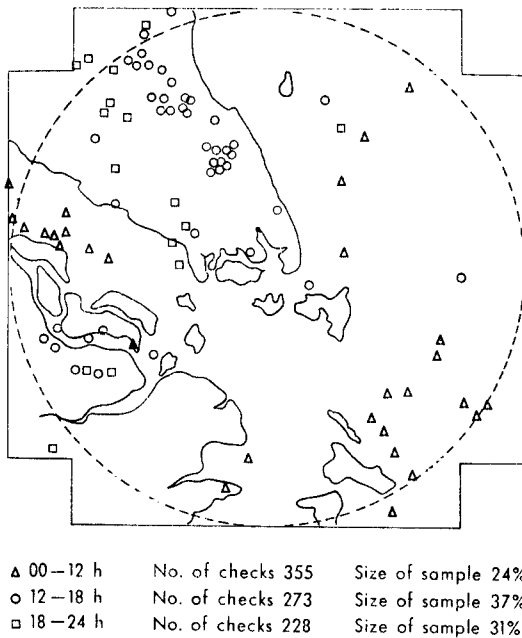


FIGURE 11—DISTRIBUTION OF ECHO-TOPS OVER 50 000 FEET IN AUGUST AND SEPTEMBER 1970

50 000 ft over the sea is much less than over the land even at the times most favourable for their occurrence; only over the Malacca Strait is there a density comparable with that over Malaya, and the China Sea (apart from coastal waters) is often free of all but a thin sprinkling of isolated tops.

The last point demonstrated by these diagrams is that over Malaya the location of the highest afternoon tops during months with a dominant wind-flow is to the lee side of the land mass. The existence of this lee effect first became apparent during the north-east monsoon of 1968–69 when, although heavy rain often affected the eastern half of Malaya, the high tops were found to be mostly confined to the west. The diagrams for the combinations November–December 1969 and January–February–March 1970 confirm this feature of the distribution; similarly, in the afternoons of September 1969 and August–September 1970, during the south-west monsoon, high tops occurred mainly over the eastern half of Malaya.

Part II of this paper will be published in March.

REFERENCES

1. ROACH, W. T. and JAMES, B. F.; A climatology of the potential vertical extent of giant cumulonimbus in some selected areas. *Met Mag, London*, **101**, 1972, pp. 161–181.
2. DONALDSON, R. J.; A demonstration of antenna beam errors in radar reflectivity patterns. *J Appl Met, Lancaster, Pa*, **3**, 1964, pp. 611–623.
3. LEE, J. T. and MCPHERSON, A.; Comparison of thunderstorms over Oklahoma and Malaysia based on aircraft measurements. *London, R Aero Soc, Int Conf Atmos Turb, London, May 1971*, London, 1971, Paper No. 3.
4. CHAPMAN, S. and LINDZEN, R. S.; Atmospheric tides, thermal and gravitational. Dordrecht, D. Reidel Publ. Co., 1970.
5. BRIER, G. W. and SIMPSON, JOANNE; Tropical cloudiness and rainfall related to pressure and tidal variations. *Q J R Met Soc, London*, **95**, 1969, pp. 120–147.

TORNADO IN SOUTH-EAST ESSEX ON 7 AUGUST 1973

By C. I. GRIFFITHS

(Meteorological Office, Shoeburyness)

Summary. The writer was alerted by the passage of a tornado, and describes the local effects, collating some evidence along its track. He suggests that heat-sources downwind may have triggered off the phenomenon, and concludes his note by discussing the meteorological situation.

The Thorpe Bay-Foulness area of south-east Essex was crossed by a tornado on 7 August 1973. The disturbance passed through a garden within 50 yards of the writer, who thereby became most interested in ascertaining its track.

It was possible to plot the tornado's path quite accurately, as the trail of damage was fairly narrow, and deviated little from a slightly curved line over the 8-mile route. Some sighting reports helped fill in gaps over open country. It is rather remarkable that the path is very similar to that of the Shoeburyness whirlwind of October 1949, as described by Hemens.¹ A sketch map of the area showing the path of the tornado is shown in Figure 1.

Damage was most severe between points A and B, and again at C. In the Thorpe Bay area (A-B) several large trees bordering the golf course were uprooted, though the roots proved to be fairly shallow. Chimney pots, roof tiles, garden walls and television aerials were brought down, and one car was reported to have been overturned. There was little evidence between B and C, though the passage of the tornado over the main A13 road south of Wakering was betrayed by numerous broken branches.

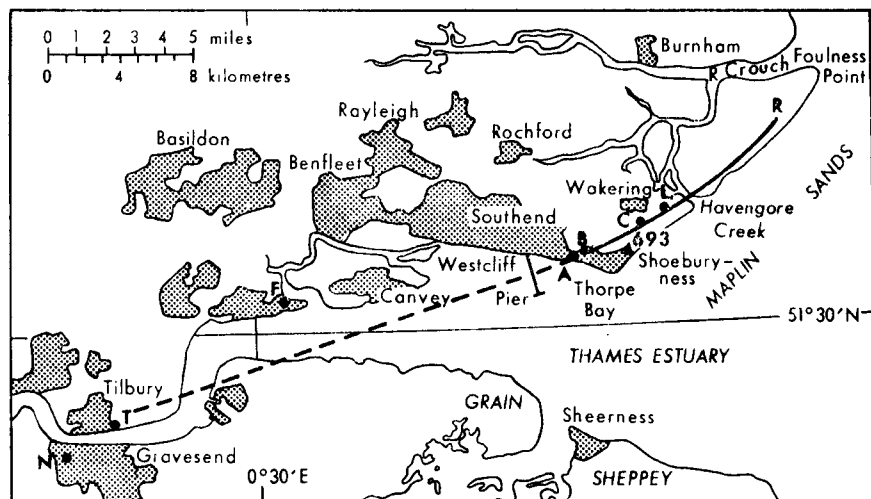


FIGURE 1—PATH OF TORNADO ON 7 AUGUST 1973

—— known track - - - suggested 'backtrack' to power stations on banks of River Thames

F position of flares at Shellhaven Refinery T Tilbury Power Station
N Northfleet Power Station

See text for explanation of other letters and figures on track of tornado.

The writer, near point C, recorded the passage of the disturbance at 0749 GMT. Cloud appeared to be swirling fairly low overhead, though it was not possible to discern a funnel cloud. Some trees, bushes, and even grass were flattened almost to the horizontal in the wind blast which preceded the whirlwind itself. It was subsequently discovered that debris was mainly deposited to the north-east of points of pick-up. One fairly large tree was broken off just above ground level, and several others were decapitated. A garden shed was shifted some 30 feet, and panes and wooden framing of adjacent glasshouses suffered severely.

Meteorological staff on duty at Shoeburyness radiosonde office (L) observed a short-lived waterspout as the tornado passed over Havengore Creek, at about 0755 GMT. The final trace was slight structural damage at Rugwood (R), some 8 miles from Thorpe Bay, at about 08 GMT.

The occurrence is of considerable interest in that it is possible that the tornado may have been produced partially by artificial means. Heat-sources are available at the flares at Shellhaven Refinery, near Canvey Island, and at power stations on the Thames Estuary. There was some backing of the known track between points A and B, rather more obvious on a larger-scale map than on the one which is reproduced here. This backing was possibly the result of increased friction over land. Rough backtracking, indicated by the dashed line in Figure 1, leads to the power station at Tilbury (T), some 16 miles west-south-west of Thorpe Bay. Inquiries have elicited the fact that pilots of light aircraft frequently report turbulence in this area. Unfortunately, no reports could be discovered of tornado sightings south-west of Thorpe Bay, nor was there any sign of damage to Southend Pier, which must have been in the tornado's path (see Figure 1). The extrapolated track is largely over water, and with showers in the area, the tornado may have travelled unobserved.

Hoddinott² describes funnel clouds near Chester in 1958 and 1959, to the lee of coke furnaces, and more recently Heighes³ has discussed the formation of miniature funnel clouds suspended beneath smoke plumes from certain factory chimneys. It would seem that observers downwind of such sources in meteorological conditions similar to those described below may well be rewarded by seeing these somewhat unusual phenomena.

Meteorological situation. A well-marked cold front had passed at 1530 GMT on the previous day, leaving the Shoeburyness area in a very unstable west-south-westerly airstream. The temperature sounding made at Shoeburyness (Landwick), only a few minutes after the waterspout had been seen, is reproduced as Figure 2. At Shoeburyness synoptic office (693) at 0756 GMT, the following conditions were reported: surface wind 260° 20 kt; rain showers; dry-bulb temperature 14·8°C; dew-point 13·4°C; barometer 1010·6 mb. Between 0745 and 0750 GMT the barograph trace showed a temporary depression of approximately 1 mb; also at this time the wind veered by some 60° and a 48-kt gust was recorded, indicating the passage of a trough. Barograph and anemograph records are reproduced as Figures 3 and 4. A thunderstorm was observed about 5 miles to the north of the area at the time of the tornado. Showers occurred at Shoeburyness throughout the morning with a thunderstorm at 1207 GMT. The sea temperature at Southend Pier was 18·5°C.

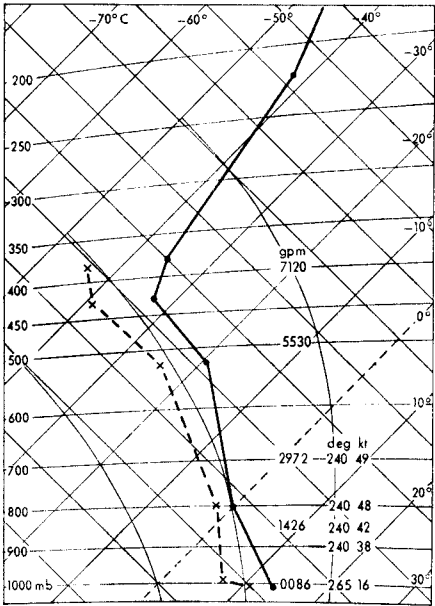


FIGURE 2—SHOEBURYNESS ASCENT DATA FOR 7 AUGUST 1973 AT 0805 GMT
· — · dry-bulb temperature x - - x dew-point temperature

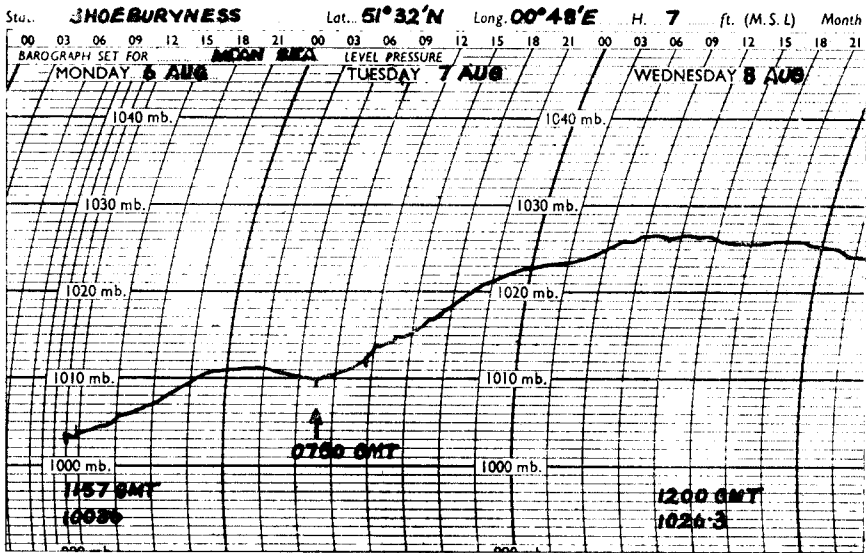


FIGURE 3—DIAGRAMMATIC REPRESENTATION OF SHOEBURYNESS BAROGRAM FOR 7 AUGUST 1973

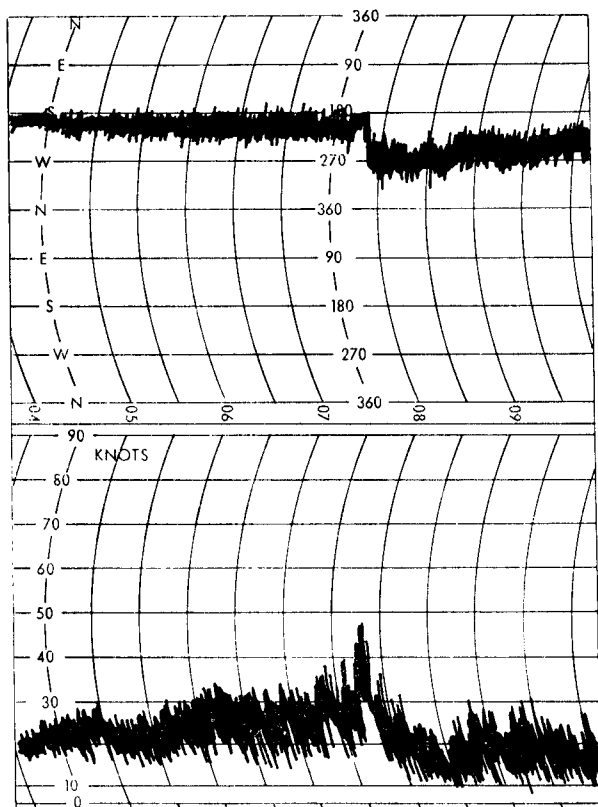


FIGURE 4—DIAGRAMMATIC REPRESENTATION OF SHOEBURYNESS ANEMOGRAM FOR
7 AUGUST 1973

Chart time is GMT.

REFERENCES

1. HEMENS, L. G.; Whirlwind at Shoeburyness. *Met Mag, London*, **79**, 1950, pp. 256-260.
2. HODDINOTT, M. H. O.; Funnel cloud at Chester, 28 July 1959. *Met Mag, London*, **89**, 1960, pp. 124-125.
3. HEIGHES, J. M.; Funnel cloud observations downwind from a chimney. *Weather, London*, **25**, 1970, pp. 289-290.

A METEOROLOGICAL/ENTOMOLOGICAL STUDY

By R. J. ADAMS

Summary. An account is given of an experiment designed to obtain temperatures at 10 cm below, near, and at 25 cm above the surface at different locations around a deciduous tree, for comparison with meteorological records from a nearby standard site. Such non-standard data are frequently needed, for example in assessing the ability of an imported pest species to survive in a climate beyond its normal geographical range.

Introduction. 'Readings of temperature and rainfall depend, to some extent, on the exposure of instruments, and if observations made at different stations are to be comparable, it is necessary to ensure that instruments are set up under as near uniform conditions as possible.' This perfectly valid statement, from the Meteorological Office pamphlet *Making weather observations* should not be interpreted as meaning that such observations are the only ones worth making.

The way in which comparable conditions for the measurement of temperature are achieved includes the exposure of instruments in a standard screen, which is itself sited in a standard enclosure in surroundings not unduly influenced by local features. For synoptic and climatological purposes a network of such sites is precisely what is required, but the information so obtained is frequently inadequate for other purposes. Expressed more simply, most processes influenced by weather in everyday life occur in places other than little white boxes 4 feet above the ground. Meteorologists are frequently called upon to comment upon such processes but find themselves with only partially relevant data. Typical of such an inquiry is a recent request from the Plant Pathology Laboratory, Harpenden, Herts., for information to help them assess the ability of insects to survive in regions outside their normal geographical range.

Entomological factors. One of the responsibilities of entomologists at Harpenden is to devise regulations to control the import of agricultural products which may carry with them potentially harmful pests. If a species cannot survive and reproduce under its new biological and climatic conditions there is no need to prohibit its entry. As has been pointed out by Baker,¹ biological factors affecting the survival of species include the availability of suitable food, the interaction between pest, predator and prey, and the structure of the plants and soil in which the species live and move. The net result of the complex interaction of these factors cannot be determined by entomologists with sufficient accuracy, so any assessment of the potential pest status of an exotic species by a method which attempts to predict the results of such interaction can be little more than a guess. The process of releasing a colony of pests into a suitable field to see how they behave is impracticable, not only because of the risks involved, but also, in the event of a negative result, because of the difficulty in identifying those particular factors which caused the failure of the species to establish itself. If these factors cannot be defined, there can be no confidence in declaring the results applicable elsewhere.

Within a limited range the rate of growth of insects increases with temperature, so laboratory experiments under controlled conditions can approx-

imately establish the effect of such parameters as day-length, mean temperature, and diurnal temperature range on the life cycle of a pest. Baker¹ has demonstrated that for some species this can be done in sufficient detail to enable the results to be used to explain, and even to predict, the timing of events in the life cycle of an insect in an outdoor environment. This is the first step in any assessment of the potential of a species in a new environment, because in order that a species shall survive, its life cycle must be adequately synchronized with the seasons so that, for example, insects are in a suitable development stage at the onset of winter. Clearly, associations derived from laboratory studies and attempts to explain meteorologically the timing of events are only of value if related to conditions occurring in possible sites for insect habitation. Although some specialist studies have been undertaken (e.g. Lewis,² in which insect emergence was related to tree-bark temperature), using the relevant physical conditions, the standard meteorological data do not provide this information.

Site, instrumentation, and purposes of experiment. In order to measure directly some suitable temperatures, a pilot experiment has been set up in the grounds of the Meteorological Office College, Shinfield Park, near Reading, at a site selected in co-operation with the Plant Pathology Laboratory. The site, comprising the area close to and immediately under the canopy of a mature pear tree (see Plate I) is of interest to entomologists, since several species of insects and larvae spend the summer months in the leaves of deciduous trees, and subsequently fall to the ground to continue their life cycle in the upper few millimetres of the soil.

Platinum-resistance thermometers with continuous remote recording have been placed at the four cardinal points, 1.5 m from the bole of the tree, and at a distance of 12 m to the west, at depths of 10 cm (for comparison with a standard soil thermometer), 25 cm above the surface, and, of most significance, in the region of roots and decayed vegetation about 0.5 cm below the surface. Initially only the northerly point has temperature probes at each of the three depths indicated. Eight probes have been deployed between the five points, and a further four probes are available to be sited following examination of the records for the first few months. It is conceivable, for example, that such examination will indicate that variation of temperature as a function of distance from the tree is of more significance than its directional dependence. Continuously recorded temperature, radiation and other data from the Meteorological Office College site about 100 m distant are available, and also daily readings of all standard climatological data from the University of Reading agrometeorological station (Shinfield) about 0.5 km to the south-east. It is hoped that in the forthcoming year or two sufficient data will have been gathered to satisfy the following aims :

- (a) To obtain quantitative measurements of localized temperature variations in a field situation of biological interest.
- (b) By examining these results in conjunction with other meteorological data, to assess the feasibility of either making appropriate adjustments to the standard-screen and grass-minimum temperatures, or estimating the magnitude of errors introduced by assuming these temperatures to be indicative of a nearby, but dissimilar, environment.

- (c) By conducting such an experiment at first hand to place the Agricultural Section of the Meteorological Office in a better position to advise other research organizations wishing to set up their own investigation into an environment in which they have particular interest.

Studies of the inter-relation between entomology and meteorology have of course already taken place (e.g. Hurst³). It is hoped that this venture will extend such interdisciplinary co-operation further.

Acknowledgements. The author wishes to thank Mr D. H. Johnson and his staff at the Meteorological Office College for their willing co-operation, and Mr C. R. B. Baker of the Plant Pathology Laboratory, Harpenden, with whom this joint meteorological/entomological study is being conducted.

REFERENCES

1. BAKER, C. R. B.; An approach to determining potential pest distribution. Paris, European and Mediterranean Plant Protection Organization. *Bulletin* No. 3, 1972, pp. 5-22.
2. LEWIS, T.; The effect of weather on emergence and take-off of overwintering *Limothrips cerealium* Haliday (Thysanoptera). *Ann Appl Biol, Cambridge*, 51, 1963, pp. 489-502.
3. HURST, G. W.; Small mottled willow moth in southern England 1962. *Met Mag, London*, 92, 1963, pp. 308-312.

AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday, 23 November 1973 at the Ministry of Defence, Whitehall. The Vice Chief of the Air Staff, Air Marshal R. L. Wade, C.B., D.F.C., presided and the Prizes and Awards were presented by the generous donor Major K. G. Groves, who was accompanied by Mrs Groves. The ceremony was attended by the Director-General of the Meteorological Office, Dr B. J. Mason, C.B., F.R.S., and by the Director of Services, Mr J. K. Bannon, I.S.O. (see Plates II-IV).

The 1973 Aircraft Safety Prize was awarded to Master Air Loadmaster M. W. Bailey of Royal Air Force Akrotiri, with the following citation :

'At RAF Akrotiri, Master Air Loadmaster M. W. Bailey is a member of No. 70 (Hercules) Squadron whose role includes a Search and Rescue (SAR) commitment.

The existing SAR role equipment on the squadron is basically that previously used in Argosy aircraft but, although operationally effective, it has been found to have shortcomings when used in the Hercules. In seeking a remedy, Mr Bailey has devised a series of modifications embracing the pyrotechnic container, the layout and accessibility of equipment inside the aircraft, and improved dispatch to survivors.

The modifications, tested and found workable, include locating the SAR role equipment in the aircraft on five pallets mounted on a roller conveyor, an arrangement which permits an aircraft role change in some 30 minutes instead of the present 5 to 6 hours. Furthermore, since the pallets are made from standard Army one-ton baseboards, the configuration could be considered for Argosy and Andover aircraft if required.

In applying himself to this worthwhile project, Master Air Loadmaster Bailey has made a valuable contribution to the RAF Safety Services and he is a worthy winner of the Aircraft Safety Prize.'

The 1973 Meteorology Prize was awarded to Mr P. Goldsmith, Senior Principal Scientific Officer, Meteorological Office, with the following citation :

'As leader of a scientific team responsible for the study of cloud physics and dynamics, Mr Goldsmith has been the inspiration and driving force behind a major series of expeditions which have exploited radar, aircraft and other sophisticated new methods in the study of the structure of rain-producing weather systems. Conducted from the Isles of Scilly these experiments have convincingly demonstrated that the rainfall pattern at fronts can be linked with the air motions on a scale of tens of kilometres. By developing new techniques of employing aircraft, dropsondes, radiosondes and radar Mr Goldsmith has forged a new tool for the investigation of the causes of the observed patterns of rainfall.

Mr Goldsmith has also played an important role in devising programmes to examine the possible impact of supersonic aircraft on the constitution of the stratosphere and has demonstrated in particular that there is no reason to expect effects upon atmospheric ozone greater than those produced by atomic bomb tests — effects which, if they exist, are too small to be detected.'

Mr Goldsmith was unable to attend, as he was a delegate at the World Meteorological Organization Commission for Atmospheric Sciences meeting in Versailles. The Prize was accepted on his behalf by Dr W. T. Roach, the recipient of the Meteorology Prize awarded in 1967.

The Meteorological Observer's Award for 1973 was awarded to Squadron Leader N. Lamb, Meteorological Research Flight, with the following citation :

'Squadron Leader N. Lamb has been Officer Commanding the Meteorological Research Flight at Farnborough since 1970. Throughout this period he has contributed greatly to the observational programme by his ability to recognize fully the scientific requirements and suggest appropriate in-flight variations of plan to meet the meteorological circumstances. During the first three months of 1973 the Canberra aircraft was detached to Boulder, Colorado to participate in a multi-aircraft project to investigate airflow disturbances over the Rocky Mountains. During the detachment a total of 37 sorties was carried out, the serviceability of the aircraft being far greater than that of any other aircraft involved. The leadership of Squadron Leader Lamb was largely responsible for the successful fulfilment of the mission.'

The Second Memorial Award for 1973 was awarded to Flight Lieutenant P. Wallis, formerly of Royal Air Force Tern Hill, with the following citation :

'One of the problems confronting a survivor in a single-seat liferaft is the removal of sea water from within the dinghy. Existing bailing arrangements require the canopy to be at least partly open and, in rough weather, more water may enter than is being removed.

Flight Lieutenant P. Wallis has proposed modifications, utilizing the existing bailer attached to a pipe through the side of the closed canopy, which permits the evacuation of sea water by gravity. The limited tests so far conducted suggest that the concept is sound and that the idea could

lead to much improved comfort and safety for the occupants of single-seat liferafts. For his resourcefulness in tackling this problem, Flight Lieutenant Wallis well merits the Second Memorial Award.'

REVIEWS

Radar observation of the atmosphere, by Louis J. Battan. 230 mm × 155 mm, pp. xvi + 197, illus., The University of Chicago Press, 126 Buckingham Palace Road, London SW1, 1973. Price: £7.15.

This book is a new version of the author's *Radar meteorology* which was published in 1959. This earlier book has been the only general account of the subject available in the English language but during the 14 years which have elapsed since its appearance there have been many significant developments, so it has become increasingly out of date. In fact the new book contains sufficient new material to justify the change of title. Professor Battan states in his preface that the book is intended primarily for use by meteorologists, atmospheric scientists, and students who have had little training in electronics, but that it should also be informative to a much broader spectrum of scientists and engineers. The book succeeds in providing an adequate summary of the principles involved in using radar in meteorological applications, and presents a wide selection of observations. The author does not go into any substantial detail in the topics discussed, so a reader particularly interested in a specific item may not find enough information to satisfy his interest, but the list of over 600 references will enable him to proceed further into the literature; his task might however have been simpler if articles published in readily accessible journals had been cited when possible, rather than contract reports or conference proceedings.

The first six chapters, constituting about a quarter of the total text, summarizes theoretical aspects of the meteorological uses of radar. The summary begins with a simple account of the principles of radar, and then discusses the properties and propagation of electromagnetic waves. This is followed by three chapters on the scattering and attenuation produced by precipitation particles, including an entire chapter on the back-scattering by melting spheres and non-spherical particles, one of the fields in which Professor Battan has specialized, but which he has perhaps overemphasized in a book of this type. There is a danger that a reader interested primarily in the meteorological applications of radar will find this first part of the book tedious. It would be a pity if this resulted in his not reading the later chapters, which summarize the wide variety of meteorological uses to which weather radars have been put. There are chapters on the uses of radar for precipitation measurement, Doppler radar, the use of radar in cloud-physics research, radar observations of medium- and large-scale systems and clear-air echo studies. This last field of investigation was in its infancy at the time of the earlier book but with the current availability to meteorologists of very sensitive radars it is now the area of most striking progress in radar meteorology.

Anyone who has found *Radar meteorology* of value will find this version more so, and anybody new to the subject would be well advised to commence his reading with this book.

T. W. HARROLD

Studies in ice physics and ice engineering, edited by G. N. Yakovlev (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem). 245 mm × 175 mm, pp. v + 192, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1973. Price: £7.50.

This book consists of 21 articles on various subjects relevant to ice technology, and is largely the work of the Arctic and Antarctic Institute of the U.S.S.R. It represents work that could only be carried out in Russia, in Canada, or in the Antarctic, and has been done by Russian scientists and engineers in an effort to apply scientific methods to the severe environment of the Arctic and the Antarctic.

The first group of articles deals with methods of estimating the strength (i.e. carrying capacity), and resistance to icebreakers, of a natural ice-cover. Theoretical and laboratory studies and observations in the 'field' are described. Formulae are given for the static pressure exerted at various depths in an ice-cover at its boundaries. The salinity of the ice and the duration and intensity of the frost are controlling factors, but the formulae are subjective and irregular with regard to sign. As one might expect, the history of an ice field greatly affects its strength and resistance to icebreakers. Ice 'covers' have been synthesized in the laboratory, and natural and artificial ice have been subjected to exhaustive electrical and mechanical tests. Ice has been considered as a building material and successfully reinforced with wood, and the performances of towed models in ice-covered tanks have been recorded.

Further articles show that ice may not be treated as a homogeneous continuum; uneven stresses, within the ice, cause cracks which make large pieces more likely to break up than small. The general orientation of the ice-crystal axes, which depends on the thermal history of the original freezing water, decides the strength of a layer of ice. Therefore the strength and character of ice fields and areas of fast ice can be classified according to geographical regions. The elastic qualities of a complete ice-cover, or very large ice floe can best be measured ultrasonically or seismically, i.e. practically instantaneously. Static methods are possible in which the slope of an ice sheet is measured by a tiltmeter in response to a heavy load placed on the ice. However, Young's Modulus measured by the latter method is less than half that measured by 'instantaneous' methods. The elastic qualities of ice depend on the period of time during which any load is applied. Theoretical studies of elastic waves in a large floating ice sheet do not appear to have produced useful practical results. One paper describes the tiltmeter, which is a precise instrument in which a pendulum is used to measure the slope of ice sheets.

There are interesting studies of the differential melting of hummocks, their static stability and underwater topography. The support and persistence of these massive pieces of ice within an ice sheet are of significant importance in ice navigation.

There are notes concerning the ice-cover in the Antarctic, particularly at the Russian Station at Mirny. Notes are given concerning the structure in depth of the ice-cover in the Antarctic, and these notes are consistent with earlier observations made elsewhere. The clear days are accompanied by intense solar radiation which penetrates the ice and is very effective in breaking it up. Successful experiments in blasting Antarctic ice are described. In another paper an efficient method of directional blasting is described.

Experiments are described in which sea water has been greatly supercooled. In nature, supercooling is very effective in the rapid formation of an ice-cover but it is shown that the degree of supercooling is relatively slight.

There are articles on the cutting of ice with hot torches and with jets of water. The torches require very careful handling as they can burn up; the jets are quite efficient and can be used from icebreakers.

The Russians have dealt adequately with the Arctic for centuries, and must have many sound, purely practical methods of dealing with ice, snow and extreme cold. This book seems to me to be a beginning and does not show that scientific methods have yet advanced sufficiently to overtake practical techniques based on long experience.

The book is well produced and the translation very clear and readable. It is unique to British readers in that it demonstrates the application of science to an environment quite different from their own. It should therefore be of great interest to all those whose work requires a knowledge of ice phenomena.

G. A. TUNNELL

LETTER TO THE EDITOR

551-509.324.2:551.578.45

Wet-bulb freezing level as a snow predictor

Mr B. J. Booth has drawn attention to the wet-bulb freezing level as a snow predictor in his recent paper.¹ Figure 2 of the paper shows that to a good approximation there is a linear relation between the snow index I_s and the height of the wet-bulb freezing level.

Bader² has also recently given an excellent example of the effect of the dryness of the air on the form of precipitation.

As long ago as 1950, Douglas³ stressed the importance of the wet-bulb freezing level as a snow predictor, and it is unfortunate that it was omitted from the list of predictors given by Boyden,⁴ especially since it is by far the most useful one on those memorable occasions when snow descends well below the initial dry-bulb freezing level.

Mr Bader and Mr Booth are therefore to be congratulated on having again demonstrated the importance of the wet-bulb freezing level as a snow predictor.

*Regional Meteorological Training Centre,
Ikeja Airport,
Lagos, Nigeria*

F. E. LUMB

REFERENCES

1. BOOTH, B. J.; A simplified snow predictor. *Met Mag, London*, 102, 1973, pp. 332-340.
2. BADER, M.; A late April snowfall in southern England. *Weather, London*, 28, 1973. pp. 251-257.
3. DOUGLAS, C. K. M.; Some problems of snow forecasting, 1950. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)
4. BOYDEN, C. J.; A comparison of snow predictors. *Met Mag, London*, 93, 1964, pp. 353-365.

OBITUARY

It is with regret that we have to record the death of Mr J. A. Miller, Higher Scientific Officer stationed at Episkopi, Cyprus, on 22 October 1973.

NOTES AND NEWS

OFFSHORE TELEMETERING BUOYS

Construction of an operational version of OBOE I, the offshore telemetering buoy, has been approved for eventual deployment in the Thames Estuary. It is hoped to include measurements of wind direction (for the first time) and possibly of visibility. Two small buoys were equipped with anemometers and magnetic-tape event recorders for use by the Fisheries Laboratory, Lowestoft during the international oceanographic exercise 'JONSDAP 1973' in the southern North Sea, which started in September 1973.

FORECASTING FOR THE TRAWLER FLEET OFF ICELAND

Responsibility for forecasting for the trawler fleet off Iceland was taken over by a meteorologist on board the Trawler Support Vessel *Miranda* on 21 September 1973. This service is expected to continue in operation until the end of April 1974.

FORECASTS FOR THE BRITISH GAS CORPORATION

At the request of the British Gas Corporation, arrangements were made for the provision of a MET GAS forecast service to the Northern Gas Board from 1 July 1973 and to the North Eastern Gas Board from 12 September 1973. Ten of the 12 Area Gas Boards now take this comprehensive service.

MAXIMUM PERMISSIBLE LOAD CURRENTS IN AN OVERHEAD TRANSMISSION LINE

At the request of the Central Electricity Generating Board an analysis has been begun of meteorological data leading to computed maximum permissible load currents in a typical overhead transmission line. The limiting factor is the conductor temperature, which is dependent on ambient air temperature, wind speed, solar radiation and electrical heating.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked "for Meteorological Magazine."

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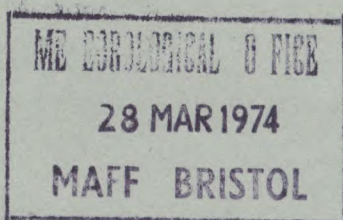
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THE DISTRIBUTION AND FREQUENCY OF HIGH CUMULONIMBUS TOPS NEAR SINGAPORE AS MEASURED BY 10-CENTIMETRE RADAR (PART II)

By F. F. HILL and R. P. W. LEWIS

(Meteorological Research Unit, Royal Radar Establishment, Malvern and Meteorological Office, Bracknell)

Summary. Radar measurements of storms near Singapore, made during 1969 and 1970, are discussed and analysed. Especial attention is given to tops above about 50 000 ft because of their importance to supersonic transport aircraft. A marked preference for development of giant cumulonimbus in certain favoured areas is described, as also are diurnal and seasonal variations of some importance.

Spatial and diurnal distribution of the higher tops. (Continued from Part I.*) It should be pointed out here that except perhaps for periods during the north-east monsoon the wind flow is rarely uniform over the whole area. The equator is only 80 n.mile south of Singapore and hence the winds over the southern portion of the area may well have a different characteristic direction from those farther north. In the south-west monsoon, for instance, the winds over Singapore and farther south are usually south-easterly and turn round into a south-westerly over Johore, often at a well-marked shear-line. (The description 'SE monsoon' is indeed sometimes used at Singapore, especially in older literature where the surface wind was the only guide.) The frequencies of surface winds from various directions for the periods September, October, and November–December 1969 are shown in Figure 12 for the three places Singapore, Malacca, and Mersing. Similar diagrams, for Singapore only, for the remaining combinations of months used for displaying distributions of echo-tops are given in Figure 13.

The formation of storms in the Singapore area is influenced by the shape of the Malay peninsula and the long, narrow strait between Malaya and Sumatra so that storms are distributed along lines rather more frequently than may be typical of equatorial regions in general. Figure 14 illustrates three examples of lines which soon become familiar. Of these, the third is the least common and least likely to be associated with high tops; it is occasionally seen in the late night and early morning when the low-level winds over the China Sea have an easterly component, and a katabatic westerly drift from the mainland sets up a convergence zone some distance off-shore. It is likely to decay

* HILL, F. F. and LEWIS, R. P. W.; The distribution and frequency of high cumulonimbus tops as measured by 10-centimetre radar (Part I). *Met Mag, London*, 103, 1974, pp. 29–48.

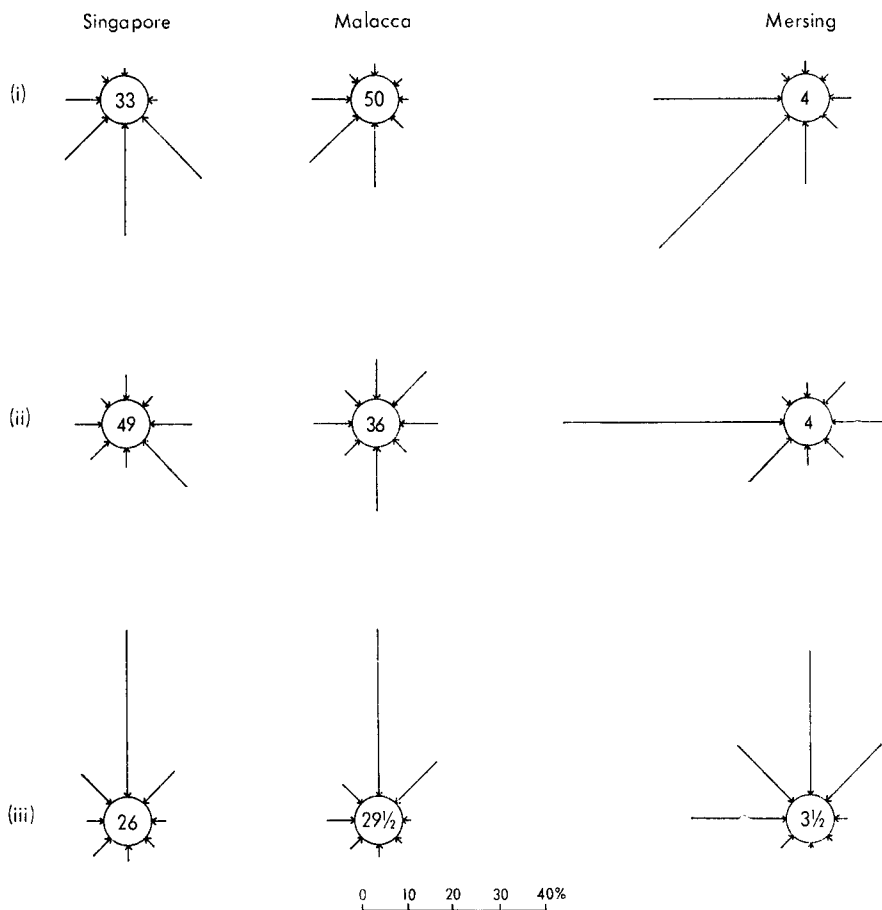


FIGURE 12—PERCENTAGE FREQUENCIES OF WINDS FROM DIFFERENT DIRECTIONS AT SINGAPORE, MALACCA AND MERSING

(i) September 1969; (ii) October 1969; (iii) November and December 1969.

Lengths of arrows are proportional to frequencies and the percentage frequencies of calms are shown in the central circles.

quickly. The second type is of frequent occurrence and the main generator of high tops. This type is subject to a variety of wind influences as already mentioned but its further development and movement should be broadly predictable.

The first figure illustrates the 'Sumatra' storm which is a night-time development and a source of major problems for the forecaster. The formation of a 'Sumatra' is largely due to convergence initiated by katabatic sinking between the parallel mountainous spines of Malaya and Sumatra. The existence of a light southerly or south-easterly wind over the strait between Singapore and Sumatra accentuates this convergence and the storms may then become a major feature with their future movement depending on the wind at low and middle levels; consequently, during the south-west monsoon the storms are likely to affect Malaya during the night or early morning.

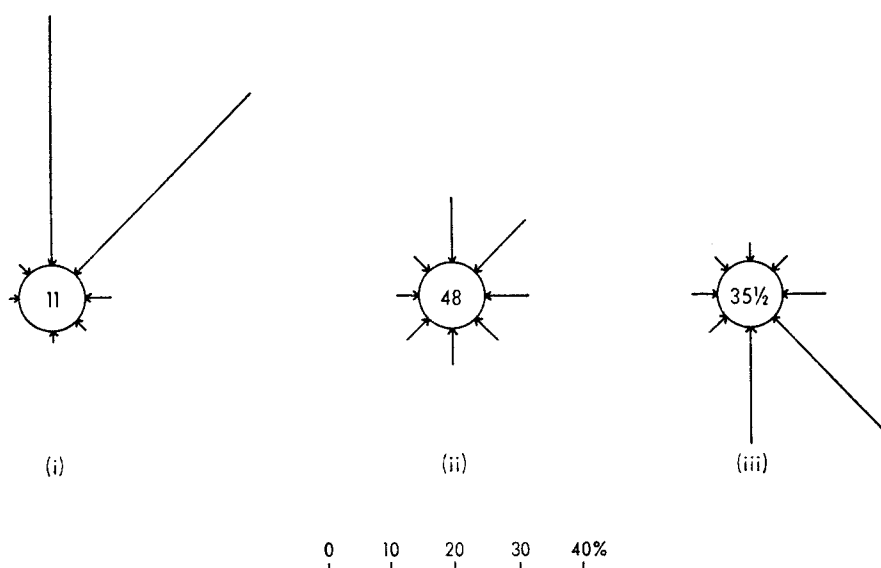


FIGURE 13—PERCENTAGE FREQUENCIES OF WINDS FROM DIFFERENT DIRECTIONS AT SINGAPORE

(i) January, February and March 1970.

(ii) April and May 1970.

(iii) August and September 1970.

See note under caption to Figure 12.

The main point of interest is, however, that the highest tops seem to be generated over the straits and near the coast only and thus have the appearance of propagating eastwards or south-eastwards in an irregular movement while the existing storms move north or north-eastwards overland and decay.

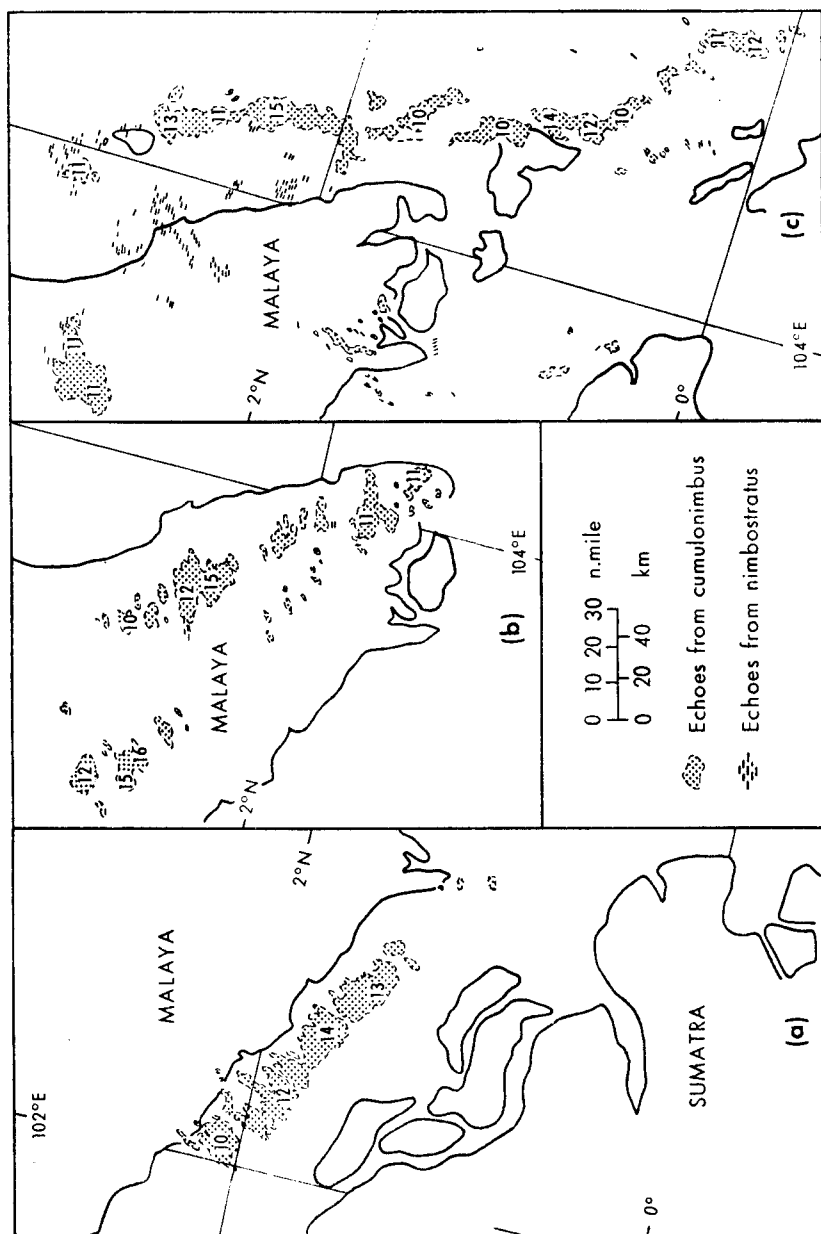
The following table gives frequencies of various types of night-time development for the period May to October in 1969 and 1970:

TABLE IX—FREQUENCY OF CERTAIN NOCTURNAL CONVECTIVE DEVELOPMENTS FOR THE PERIOD MAY TO OCTOBER IN 1969 AND 1970

Night-time echo distribution over Malacca Strait	Number of nights May–October 1969	Number of nights May–October 1970	Total
Nil or only isolated echoes	14	19	33
Several echoes, some strong, but no line	9	7	16
Numerous echoes, including formation of a line	9	9	18
Total	32	35	67

Of the 18 lines, 13 moved into Malaya. Not all the lines yielded high tops: it seemed that the more mobile the line, the less likely were they to do so; on the other hand, some of the more scattered developments generated giant Cb.

Since night-time observations were made on only about 40 per cent of possible occasions, it follows from these figures that either areas or lines of major storms with a possibility of giant Cb may be expected on about $(34/2) \times (100/40) \approx 40$ nights during the period May–October with the main activity usually occurring between 0100 and 0600 local time.



Relative frequency of heights of high tops. Figure 15 shows the relative monthly frequencies of heights of the highest top at each routine check for all tops above 6 km with separate plots for the 'afternoon' (1200–1800 local time) and for 'other times'. The curves have been subjectively smoothed to eliminate variations in the original graphs which were plotted in 0.5-km steps. A figure within the curves indicates the percentage of checks at which there was at least one top above 6 km (20 000 ft).

The graphs for 'other times' show a marked peak of frequency in most months at a height varying from 10 to 12.5 km (33 000 ft to 41 000 ft). In some months this level is the most frequent for the highest tops in the afternoon also, but the formation of giant cumulonimbus overland causes at least one secondary peak to appear at from 14 to 16 km (46 000 to 52 000 ft) and this level becomes the principal one in the more active months; in several months there was also substantial activity at even higher levels (16–18.5 km, or 52 000–60 000 ft).

In Table VIII (p.40) the numbers of echo-tops above 40 000, 50 000 and 60 000 ft are given as percentages of the number of tops above 35 000 ft, a height which is near the normal cruising level for subsonic passenger aircraft and is also near the height attained by most cumulonimbus tops over the sea and by the tops of many of the less vigorous cumulonimbus occurring over the land; again, separate figures are given for the 'afternoon' and for 'other times'. Although this method of presentation eliminates the month-to-month variation of total activity (plausibly measured by the number of tops over 35 000 ft), the table still shows some significant variations at high levels: the percentages at 50 000 ft, for example, vary from 0 to 18 per cent in the afternoons, and from 0 to 12 per cent at other times. Both zero values occurred in February 1970, the last three weeks of which were rainless in Singapore and over much of southern Malaya. It is likely therefore that convective activity was much less in this month than usual; however, relative frequencies at 50 000 ft were below 5 per cent in some other months which were not particularly dry, for example December 1969. It is consequently not possible to give one distribution curve for all months and times of day that would be of much practical use or meteorological relevance, and so two curves are illustrated in Figure 16, one of which is typical of the night, morning, and the quieter afternoons and has a decrease of frequency with height which is roughly exponential, with zero-level at about 61 000 ft; the other curve shows a distribution of frequency more typical of afternoon in the more active months: the percentages above 45 000 ft are from two to three times as high as those given by the first curve and fall to zero at about 63 000 ft.

Comparison of densities of high tops over land and sea. As the frequency distribution of heights of echo-tops for times other than 1200–1800 local time is dominated by the tops occurring in the period 0001–1200, and as most of the tops observed in this period are over the sea and coastal areas rather than inland, it is likely that the peak shown on the graphs in Figure 15 for 'other times' gives a good indication of the most usual height of the highest cumulonimbus over sea areas, i.e. typically 11–12 km (36 000–40 000 ft); this estimate is well supported by aircraft reports on the route between Singapore and Gan.

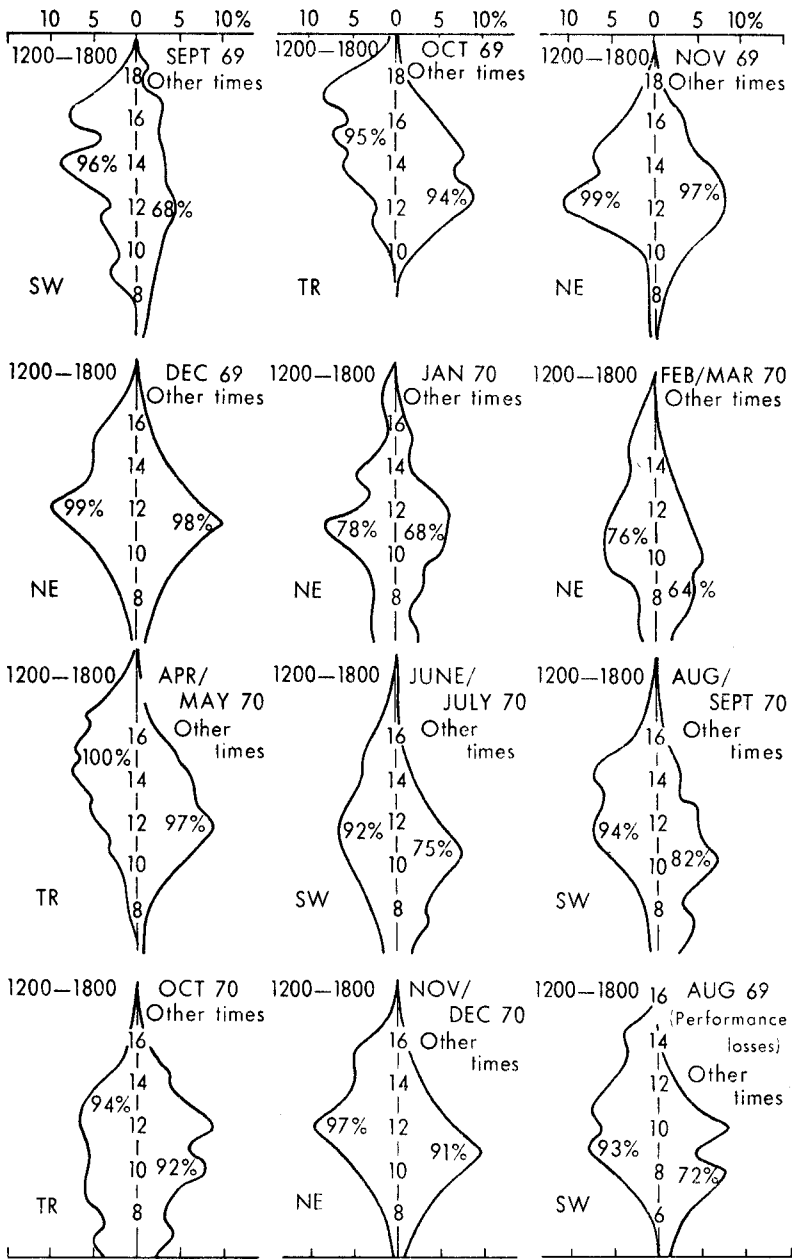


FIGURE 15—FREQUENCY DISTRIBUTIONS OF HEIGHTS OF HIGHEST ECHO-TOP OBSERVED AT EACH ROUTINE CHECK, BOTH FOR 'AFTERNOONS' (1200—1800) AND 'OTHER TIMES' FOR VARIOUS MONTHS AND COMBINATIONS OF MONTHS

Numbers on vertical axes represent heights in kilometres.

SW south-west monsoon; NE north-east monsoon; TR transitional.

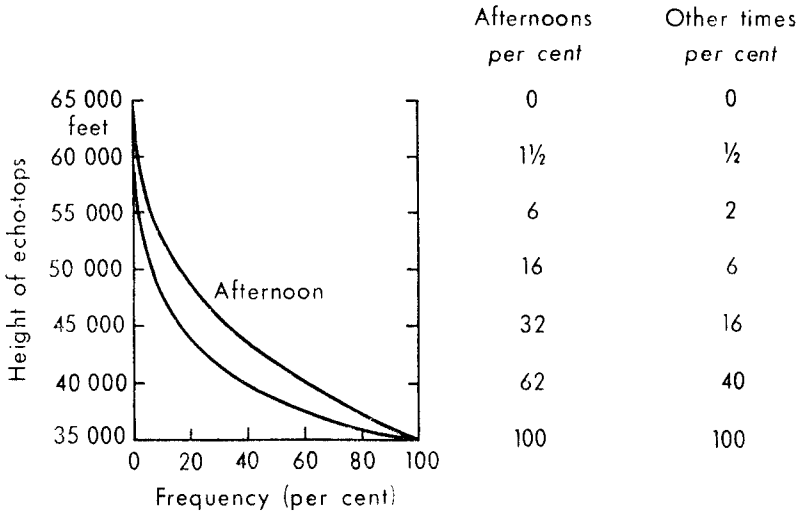


FIGURE 16—CUMULATIVE FREQUENCY DISTRIBUTIONS OF ECHO-TOPS EXCEEDING 35 000 FEET IN HEIGHT FOR 'AFTERNOONS' AND FOR 'OTHER TIMES'

The curves are applicable to the more active months.

So that the frequency of occurrence of high tops over the open sea might be estimated separately, a special area was defined lying to the east of a boundary which ran from north-north-west to south-south-east about 20 nautical miles off the east Malayan coast and avoided the large islands to the south; this area lay over the China Sea and had a size of about 13 000 (n.mile)². During 15 months of good radar performance this area was surveyed on nearly 6000 occasions and 125 tops of 50 000 ft or above were recorded; this is roughly equivalent (assuming homogeneity in time and space) to a density of one top of 50 000 ft or higher per 600 000 (n.mile)². If such tops were scattered randomly (which is not necessarily true) then an aircraft on a flight of 2000 n. mile over the open sea with a safety margin of 10 n.mile on either side would encounter such a top on 1 flight in 15. However, over 80 per cent of these tops occurred between 0001 and 1200 local time, suggesting a considerably higher incidence within this period over the open sea; this contrast may not be so evident well away from land influences because it is possible that day-time ascent and night-time subsidence causes a reciprocal effect over the China Sea within the area scanned by the radar. For the sake of comparison, the corresponding figures for the number of tops over Malaya were also derived: these were found to be one top of 50 000 ft or higher per 110 000 (n.mile)² over the whole 24 hours and one top per 30 000 (n.mile)² in the afternoon. One might have expected this last density to be greater, but the frequency of high tops is variable at all seasons, even in the south-west monsoon and transitional months, and is particularly so in the north-east monsoon.

Variation of height of storm-tops with time. The height of the top of a vigorous cumulonimbus will vary rapidly with time, especially while the cloud is still growing; of particular importance is the growth of individual

high tops in or near an area of existing storms. Time-height sections (Figure 17) have been compiled from measurements made at two-minute intervals of the principal tops of cells associated with a slow-moving storm cluster on each of two occasions. The wind-fields for one of these occasions (4 March 1970) are illustrated in Figure 18. Low-level north-easterlies over the China Sea extended across Malaya but backed to north over south Malaya and over the Malacca Straits so that there was convergence over the west coast due both to deceleration and to curvature; the main winds were light enough to allow westerly sea-breezes over this coast. The upper winds veered slowly with height, with south-easterlies established (as usual at this season) at mid-tropospheric levels. This type of pattern is common during the north-east monsoon, but it can be seen that whether storms will develop depends largely on the strength of the low-level winds. In this case, small convection cells formed well inland from the west coast, but it was not until late afternoon that the main storms developed and propagated slowly south-eastwards along the coast.

During most of the period of three or four hours during which each case was observed there were cells reaching 30 000–40 000 ft, but at intervals of

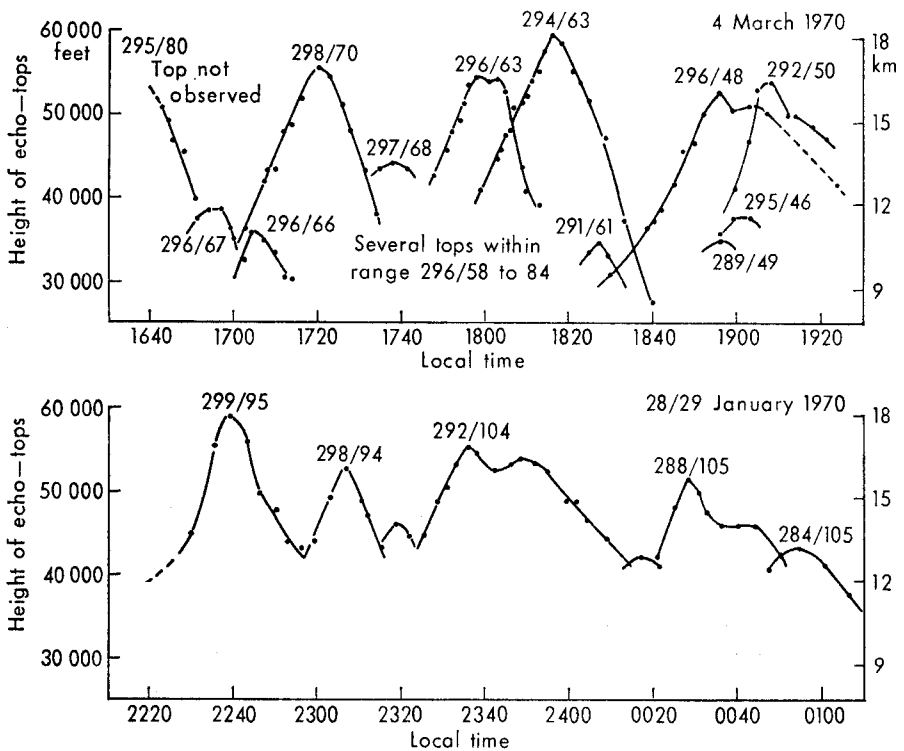


FIGURE 17—VARIATION WITH TIME OF HEIGHT H OF PRINCIPAL ECHO-TOPS OVER THE WEST COAST OF JOHORE ON TWO OCCASIONS

Bearings in degrees true and ranges in nautical miles are given in the form 295/80.

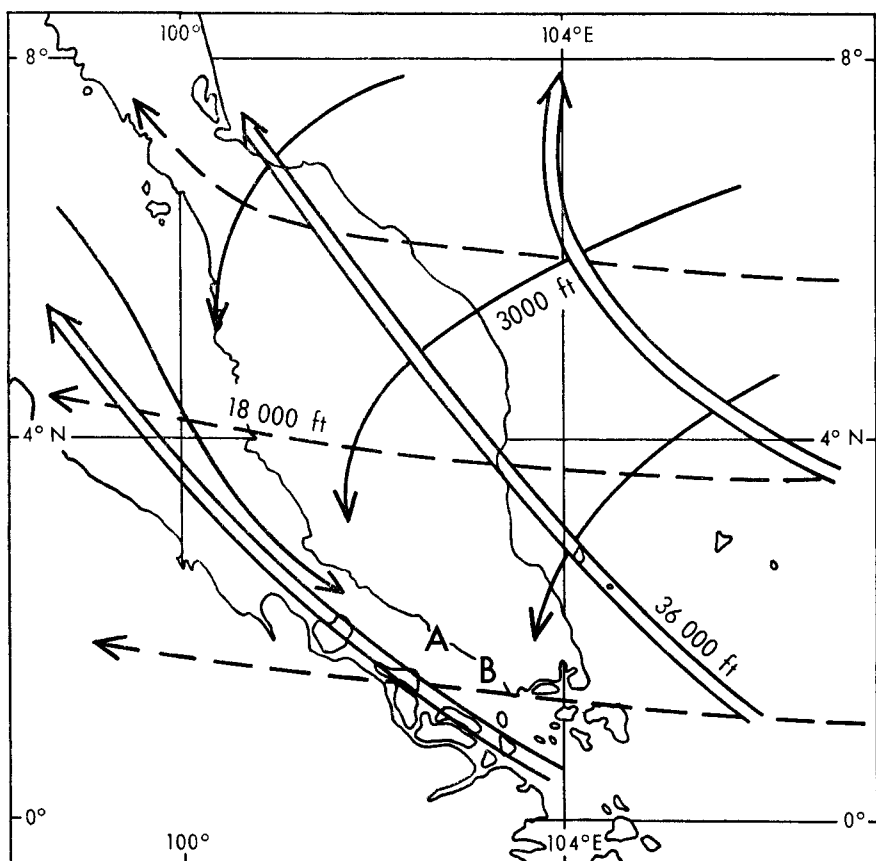


FIGURE 18—STREAMLINES AT THREE LEVELS OVER MALAYA ON 4 MARCH 1970

High tops formed between A and B and propagated south-eastwards. See also upper curves in Figure 17.

half an hour or so, individual cells grew well above the general top and reached 50 000–60 000 ft for short periods (typically 10 minutes) before subsiding. As the radar would not detect cloud left behind during decay and subsidence a good deal of cirrus and cirrostratus would probably remain for some time to hide the main cells from the view of pilots, especially if the latter were approaching from the west.

The slopes of the graphs of the ascending echo-tops suggest rates of ascent of about 1000–1500 ft a minute; this may be a useful figure for aviators to bear in mind even if more vigorous growth may occasionally be observed. (Rates of rise exceeding 1 km or 3000 ft a minute have in fact been observed on a small number of occasions.)

Relationship of echo-tops to tropopause. The highest tops observed during the periods of frequent measurement described in the last section coincided closely with the tropopause, the height of which can vary from 14.5 to 18.5 km (48 000 to 60 000 ft) but which usually lies between 16 and

17 km. However, the height of vigorous cumulonimbus can exceed that of the tropopause by a considerable margin as may be demonstrated by considering some of the highest tops observed during the present investigation. Sixteen echo-tops of at least 19.0 km in height were selected, and the height of the tropopause at the time of observation of each one was estimated from the upper-air soundings at Singapore at the beginning and end of the day in question. The mean echo-top height was 19.8 km (ranging from 19.0 to 21.0 km) while the tropopause was on average 3.5 km lower, the difference in height ranging from 1.3 to 5.4 km.

Conclusions. Although the present study is based on a relatively small proportion of the data accumulated during the investigation at Singapore, and although only methods of visual examination of the original records have been used (as distinct from computerized studies of digitized versions of the data), nevertheless some conclusions can be drawn that are of general interest to pilots and operators of aircraft flying over and near south Malaya.

Cumulonimbus tops at 55 000 ft and above may occur at any time of day or night, but are rare except during the afternoon; to have more than 2 or 3 tops over 50 000 ft occurring simultaneously within a circular area of radius 120 nautical miles is rare at any time. A few tops may penetrate the tropopause, thus exceeding 21 km (or 69 000 ft) at times; the number of tops, however, drops off rapidly with height above 12 km (or 40 000 ft) which is the most common height of tops over land during the afternoon, although tops tend to be higher by a few kilometres during inter-monsoon periods. Activity is more prevalent over the sea during the night and early morning, and over the land during the afternoon; the density of cumulonimbus over the sea, however, is at no time of day as great as it is over the land during the afternoon. Activity over Malaya tends to be concentrated on the lee side when the wind has a consistent direction, and this effect is particularly marked during the north-east monsoon.

The tops of developing cumulonimbus often rise at the rate of from 1000 to 1500 ft a minute and occasionally at rates exceeding 1 km or 3000 ft a minute.

Acknowledgement. The authors wish to express their gratitude to Mr Teo Teck Kiang for his invaluable assistance in making a large proportion of the measurements discussed in this paper.

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INDICATORS OF MONTHLY MEAN TEMPERATURE AND RAINFALL FOR ENGLAND AND WALES BASED ON ANTECEDENT MONTHLY PRESSURE ANOMALIES OVER THE NORTHERN HEMISPHERE

By R. MURRAY

Summary. From an analysis of nearly 100 years of monthly mean pressure data over the northern hemisphere, objective indices representing anomalous features of the atmospheric circulation in the preceding three months are shown to be related to monthly mean temperature and monthly rainfall over England and Wales. Useful predictions of rainfall and temperature on the monthly time-scale can be made objectively.

Introduction. In three recent papers^{1,2,3} the author has employed monthly mean pressure anomalies over the northern hemisphere to obtain empirically based predictors of seasonal rainfall and temperature for England and Wales. The same method has been employed to derive statistical relationships between simple parameters based on monthly mean pressure anomalies in antecedent months and monthly rainfall (in terciles) for England and Wales, and monthly mean temperature (in quintiles) for central England. The procedure used in the present investigation is exactly as described in detail in Murray¹ and need not be fully repeated here.

Briefly, for each class of month (e.g. as specified by quintiles of monthly mean temperature in central England), the composite monthly mean pressure anomaly maps for the three antecedent months were examined for areas where the monthly mean pressure anomaly (PA) or the PA difference between two grid points (PAD) is apparently different from zero. These PAs and PADs constitute potential predictors. Individual PAs and PADs were then selected as primary indicators, provided that they satisfied certain criteria as given in Murray,¹ but also repeated below for convenience. The pressure anomaly data in the antecedent months were ranked in order of magnitude and related to the quintiles of temperature or terciles of rainfall in the forecast month. The PA and PAD indicators were then selected from classes of the ranked pressure anomaly distribution provided that the following conditions were satisfied :

- (a) The class must contain at least 15 years; (the only exception was in connection with November temperature, see Table I).
- (b) If both ends of the distribution of pressure data appear to have an association with subsequent monthly rainfall or temperature then the Sutcliffe Score (see Murray¹) for each class must be equal to or greater than 1.2.
- (c) If only one end of the ranked pressure distribution appears to have an association with subsequent monthly rainfall or temperature then the Sutcliffe Score for each class must be equal to or greater than 1.4.
- (d) For practical purposes the pressure class was taken so that the critical pressure anomaly boundary was a whole number (e.g. pressure anomaly > 4 mb) provided also that (a) and (b) or (c) were satisfied.

The selection procedure for primary PA or PAD indicators was objective in most respects. However, on some occasions PA (or PAD) indicators, clearly representing similar features of anomalous circulation, were derived from different grid points in the same general region; in such cases a subjective selection of the indicators was made. On a few occasions, notably prior to September and October, there was an excessive grouping of all or nearly all the years of the data within the class in certain areas and in certain epochs, and these cases were omitted. This clustering of data was probably due to serious uncertainties in the basic data in some cases (e.g. in the Pacific in the nineteenth century) but may also have been a result of longer-period secular changes in circulation.

The predictive rules. The primary PA and PAD indicators were combined to produce predictors of monthly rainfall. Calling D, A and W the numbers of primary indicators of 'dry' (actually satisfying the critical pressure anomaly for a bias to tercile 1 in the distribution of rainfall terciles in the forecast month), 'average' (i.e. bias to tercile 2) and 'wet' (i.e. bias to tercile 3), then simple relationships involving mainly the number D and W but occasionally A were derived for use as predictive criteria. One example, for use in forecasting April rainfall, is given in Table I.

TABLE I—RULES FOR PREDICTING MONTHLY RAINFALL IN TERCILES FOR ENGLAND AND WALES FOR APRIL, BASED ON MONTHLY MEAN PRESSURE ANOMALY PARAMETERS IN SOME OR ALL OF THE THREE ANTECEDENT MONTHS

I	II	III	IV	V	Terciles		
					1	2	3
January	1 30 50	> 3W	January	1 D=0, W>3	5	1	14
	2 65 70	< -5W		2 W=0, D>1	17	16	4
	3 65 70	> 3D					
	4 35 50-65 70	< -3D					
	5 35 50-65 70	> 2W					
	6 60 20E-65 70	< -6D					
	7 60 20E-65 70	> 7W					
February	1 80 60E	< -1W	February	1 D=0, W>3	1	2	12
	2 80 60E	> 4D		2 W=0, D>1	20	13	3
	3 35 20	> 5W					
	4 25 150	> 2W					
	5 40 20-80 40E	< -2D					
	6 40 20-80 40E	> 4W					
March	1 25 140	< -1D	March	1 D=0, W=1	6	5	14
	2 35 10	< -3D		2 W=0, D>2	13	8	1
	3 35 10	> 1W	January + February	1 D-W<-2	4	5	29
	4 60 30E	> 5D		(D-W<-5)	(1)	(1)	(13)
	5 35 10-60 30E	< -6D		2 D-W>-1	30	24	5
			February + March	(D-W>4)	(10)	(5)	(1)
				1 D-W<-3	1	0	16
			January + February + March	2 D-W>2	20	9	1
				1 D-W<-3	2	1	26
				2 D-W=-2/-1	4	6	6
				3 D-W>0	28	22	2
				4 W>2, D=0	0	0	16
				5 D>1, W=0	12	6	0

Headings I-V have the following meanings :

- I Month and reference number of pressure anomaly (PA) indicator.
- II Position of PA or PA difference (PAD); 60 30 is 60°N 30°W, 75 100E is 75°N 100°E.
- III PA or PAD at position given in column II required to be satisfied to give the indicated bias (D=dry, A=average, W=wet) in the forecast month.
- IV Reference number of forecast rule based on the specified month or months.
- V Here D, A and W are the numbers of PA or PAD indicators which are satisfied in the specified month or months in column IV and have the bias given by the specified letter in column III. When the criteria shown under V are satisfied, the forecast probability is suggested by the distribution of monthly rainfall terciles in the last column headed 'Terciles'.

The use of the rules is illustrated in Table I. Similar tables for use in predicting general rainfall for other months of the year for England and Wales (and also for predicting mean monthly temperature for central England) are also available in an unpublished paper by Murray.⁴

Concluding remarks. Once more it should be stressed that the details of the general procedure and the underlying arguments for using monthly mean pressure anomalies as simple indices of broad-scale anomalous circulation are given fully in an earlier paper by the author.¹ The method is empirical and can give only a statistical indication of rather broad categories of weather.

By the nature of the selection process it is not possible to apply the usual statistical tests of significance to the various distributions of terciles and quintiles. Most of these distributions would of course be highly significant if statistical tests (e.g. chi-square test) were applied on the assumption that the degrees of freedom were, say, 8 for a 3×5 table or 4 for a 3×3 table.

As the various rules began to be developed they were put to the test in the actual situations which arose in preparing the operational *Monthly Weather Survey and Prospects*. The forecasts based only on these rules, but made before the event from January 1972 to March 1973, have provided a mean Sutcliffe Score of 1.8 for rainfall and also 1.8 for temperature. In the individual forecasts it is worth mentioning that only in one month, namely September 1972, were rainfall and temperature predictions simultaneously seriously wrong (i.e. as defined by negative Sutcliffe Scores). September 1972 was a very cool (quintile 1) dry (tercile 1) month (only 1894 and 1912 in the past 100 years were similar in the rainfall and temperature combination); the rules suggested incorrectly that September 1972 would be rather warm with average rainfall. It is possible that unusual combinations of rainfall and temperature will be difficult to predict by this method. However, the evidence for this is not clear. For instance, the rather cool, dry August of 1972 was correctly predicted, although rather cool (quintile 2) Augusts are usually associated with average or wet (tercile 2 or 3) weather and dry (tercile 1) Augusts with warm or very warm (quintile 4 or 5) weather.

Simple statistical methods like the present anomaly procedure can at best give only a rough indication of the likelihood of the broad patterns of rainfall and temperature on the monthly time-scale. Many other physical factors need to be taken into account. There is every expectation of a radical improvement in long-range forecasting on the monthly time-scale provided that we can increase our rudimentary understanding of the physical processes involved in the production of large-scale weather anomalies. Understanding should go hand in hand with improved numerical models of the global circulation of the atmosphere and oceans.

REFERENCES

1. MURRAY, R.; An objective method of foreshadowing winter rainfall and temperature for England and Wales. *Met Mag, London*, **101**, 1972, pp. 97-110.
2. MURRAY, R.; Prediction of summer rainfall and temperature for England and Wales from anomalous atmospheric circulation in spring. *Met Mag, London*, **101**, 1972, pp. 253-264.
3. MURRAY, R.; Forecasting seasonal rainfall and temperature for England and Wales in spring and autumn from anomalous atmospheric circulation over the northern hemisphere. *Met Mag, London*, **102**, 1973, pp. 15-26.
4. MURRAY, R.; Monthly pressure anomaly rules for predicting monthly rainfall and temperature for England and Wales. London, Meteorological Office, 1973. (Unpublished, copy available in Meteorological Office Library, Bracknell.)

THE METEOROLOGICAL TRANSMISSION SYSTEM OPERATING BETWEEN BEAUFORT PARK AND METEOROLOGICAL OFFICE HEADQUARTERS

By K. J. T. SANDS and D. G. WILKINSON

Summary. A data-transmission system has been developed by the Operational Instrumentation Branch for the display of meteorological data from remote sites. This is known as the Continuous Automatic Remote Display system. The first equipment has been operating between the official observing site at Beaufort Park and the main Headquarters building in Bracknell. The system is versatile and will have wider applications within the Meteorological Office.

Introduction. Before work started on the new Richardson Wing at Meteorological Office Headquarters Bracknell, temperature measurements had been taken from a thermometer screen located to the east of the Headquarters building, and the data displayed on dials in the entrance hall of this building, and on a potentiometric recorder in the Central Forecasting Office (CFO). Wind-speed and direction data were obtained at the Experimental Site (now Beaufort Park) and transmitted by an experimental telemetry system to dials in the entrance hall and to an anemograph in CFO. The loss of the observing site near the Headquarters building and the poor performance of the wind telemetry system led to a requirement being stated for a new system which would permit several variables to be measured at Beaufort Park and to be transmitted to the Headquarters building.

This new requirement called for :

- (a) Local display of data for the observing staff at Beaufort Park.
- (b) Remote recording of values of wind and temperature data in CFO.
- (c) Remote indication of values of wind, temperature and, possibly, visibility data in the entrance hall at Headquarters.

It was subsequently agreed that the entrance hall display would incorporate an indication of visibility and the value and time of the maximum gust in each hour.

The general approach adopted to meet the requirement was to use commercially available telemetry equipment which had already been incorporated by the Operational Instrumentation Branch into other instrument systems, together with techniques recently developed for the Mk V wind system¹ and the Digital Anemograph Logging Equipment (DALE). The standard telemetry modules known as Teleshift, Teleducer and Telecode permit data to be transmitted over a single, permanently connected, Post Office private line. Other cables of similar electrical performance could be used but repeaters would be required if the distance were greater than 30 miles. The new system has been designated the Continuous Automatic Remote Display (CARD) system.

General description. The equipment consists of three main parts (see Plates II-IV):

- (a) The data transmitter.
- (b) The data receiver and CFO display.
- (c) The entrance hall display.

The temperature measurements are made in a standard enclosure at Beaufort Park. The wind data are derived from a Mk V cup generator and a Mk IVG wind vane mounted on a 10-m mast to the west side of the site. Visibility measurements are obtained from the transmissometer on the site. The CARD transmitting equipment is housed in a room in a new block at Beaufort Park overlooking the observing area. A local display of the data being transmitted is provided for the observing staff of the Observational Requirements and Practices Branch at Beaufort Park.

The receiving equipment is housed in a wooden console in the Central Forecasting Office. Two recorders are provided :

- (a) A dual-pen chart recorder for wind speed and direction.
- (b) A 12-channel recorder for the remaining data.

No meter display is provided in CFO, but there is ample capability in the equipment if this is required at a later date.

Processed data are fed via a multicore cable from CFO to the Headquarters entrance hall display. Here the data are scaled to a suitable format for display on digital meters. The extraction of the speed and time of the maximum gust from the raw wind-speed data also takes place in the equipment located in the entrance hall. Spare capacity has been provided for additional data at a later date. The resolution of the system is ± 0.1 per cent of full scale; the corresponding accuracy is not worse than ± 0.2 per cent and will usually be better.

The data transmitter. A block diagram of the data transmitter is shown in Figure 1. The a.c. output from the cup generator is processed by circuits developed for the Mk V wind system.¹ Since the frequency is linearly related to wind speed, it is used in preference to the amplitude of the voltage. In the Mk IV wind system, which is an improved version of the Mk II wind system,² rectification of the signal leads to a non-linear relationship at low speeds. A frequency-to-voltage conversion of the generator output gives a voltage range of 0–10 volts for a wind-speed range of 0–200 knots. This voltage is fed to the Teleducer unit via a potential divider. The Teleducer unit converts the voltage input to a frequency output of 5–25 Hz, which is used to modulate the frequency of the 2340-Hz carrier of the Telshift unit. In this way, wind speed is transmitted continuously over the Post Office line, thus meeting one of the requirements of the user.

The remaining data channels are not transmitted continuously; an electronic switch (known as a multiplexer) being used to switch them sequentially. Each of the sensor outputs, including wind direction, is processed to give an analogue voltage in the range 0–10 volts. Wind-direction data are derived from a Mk IVG wind vane, again using circuits developed for the Mk V wind system, by measuring the difference in phase between the waveform obtained from the magflip rotor and a pre-set reference. When a local three-phase oscillator is connected to the stator windings of the magflip, the phase of the induced voltage is proportional to the angular position of the rotor. To avoid full-scale swings of the output indicator when the direction changes through north, the range of the direction scale is increased to 540 degrees. When the indicated direction reaches either end of the 540-degree scale, electronic switching adds or subtracts 360 degrees.

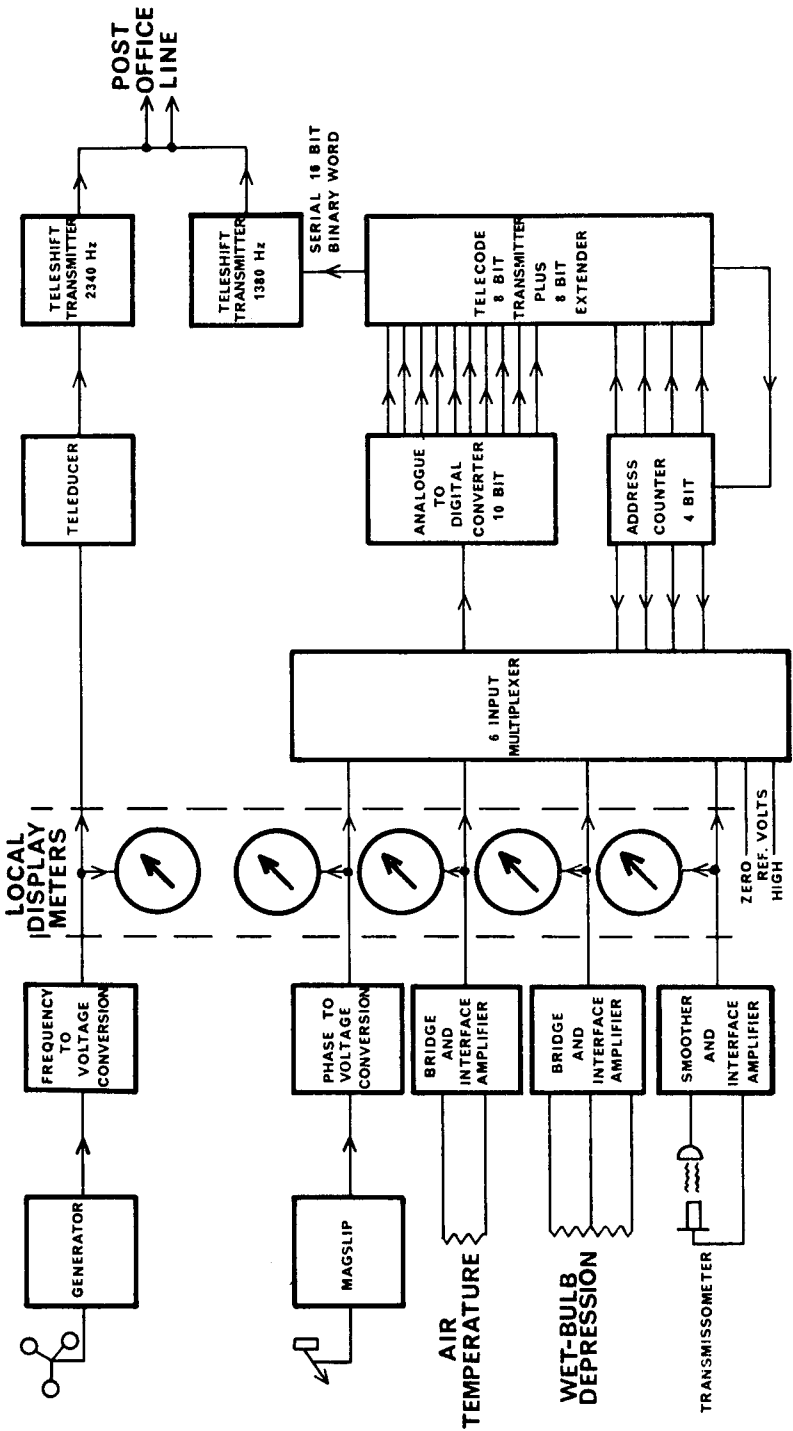
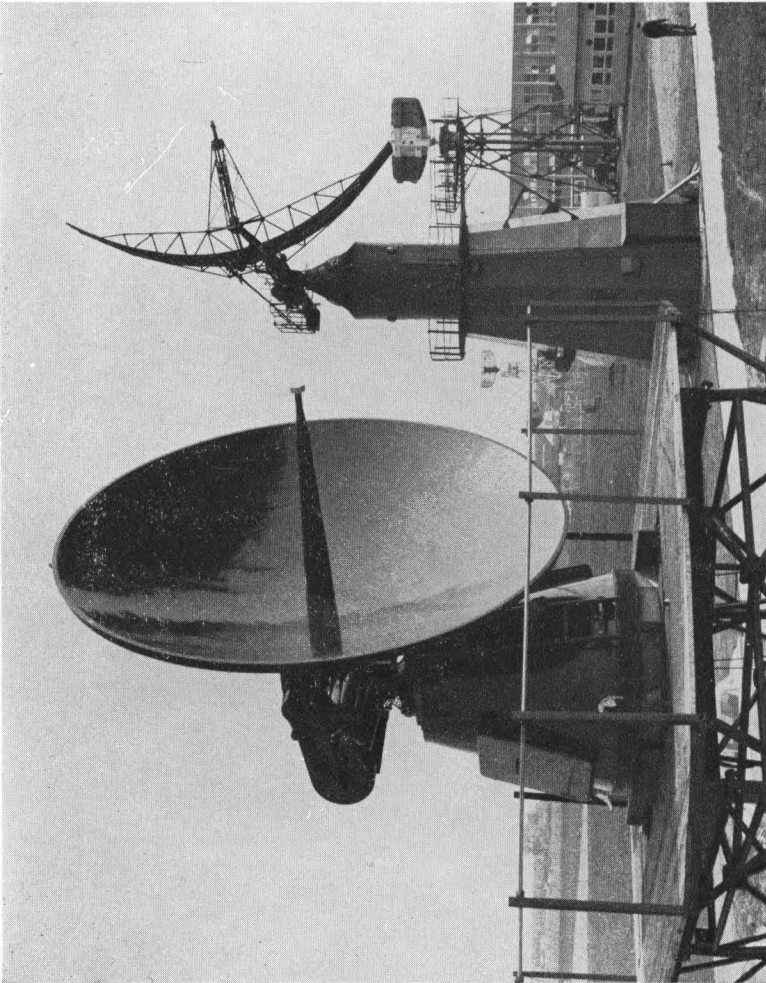


FIGURE 1—CARD DATA TRANSMITTER



Photograph by courtesy of Plessey Radar Limited

PLATE I—PLESSEY 43S 10-CENTIMETRE RADAR

A radar of this type was used for the Singapore radar project described on pp. 61-70.



PLATE II—CARD TRANSMITTER UNIT

See page 74.

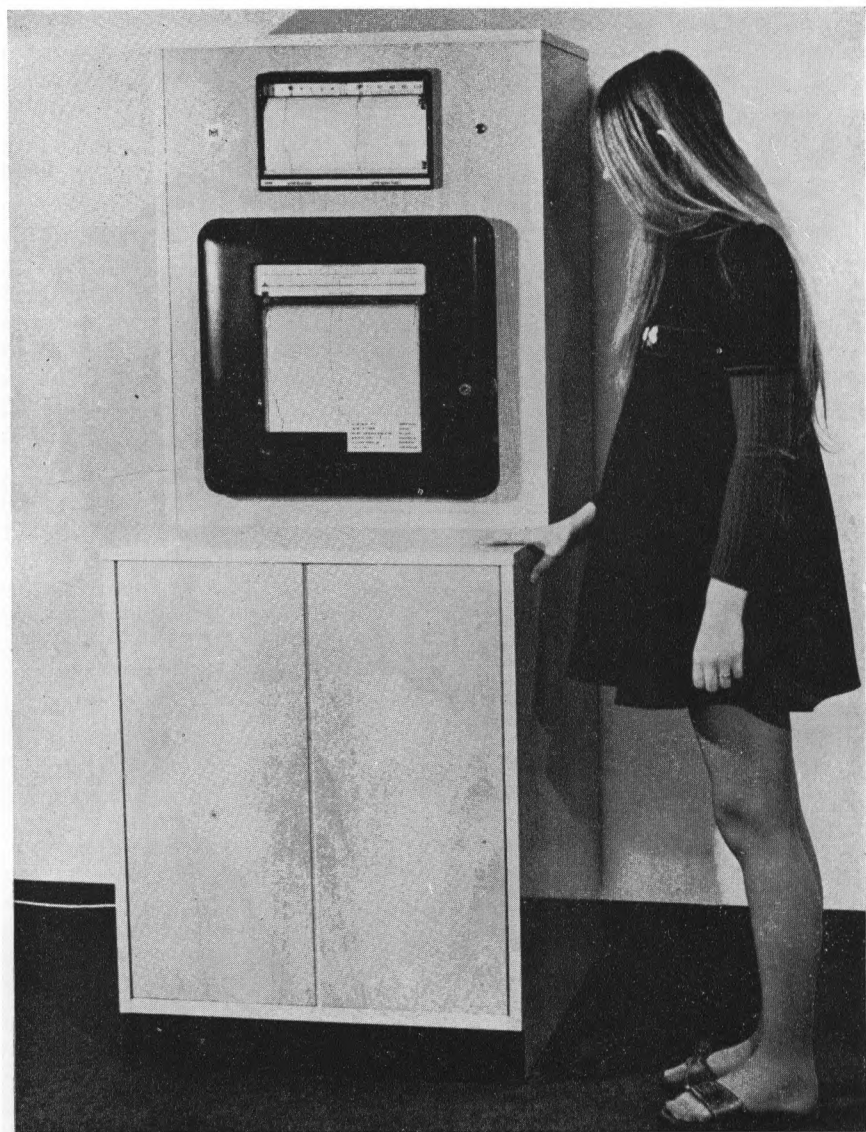


PLATE III—CARD RECEIVING UNIT AND DISPLAY IN CENTRAL FORECASTING
OFFICE, BRACKNELL

See page 74.

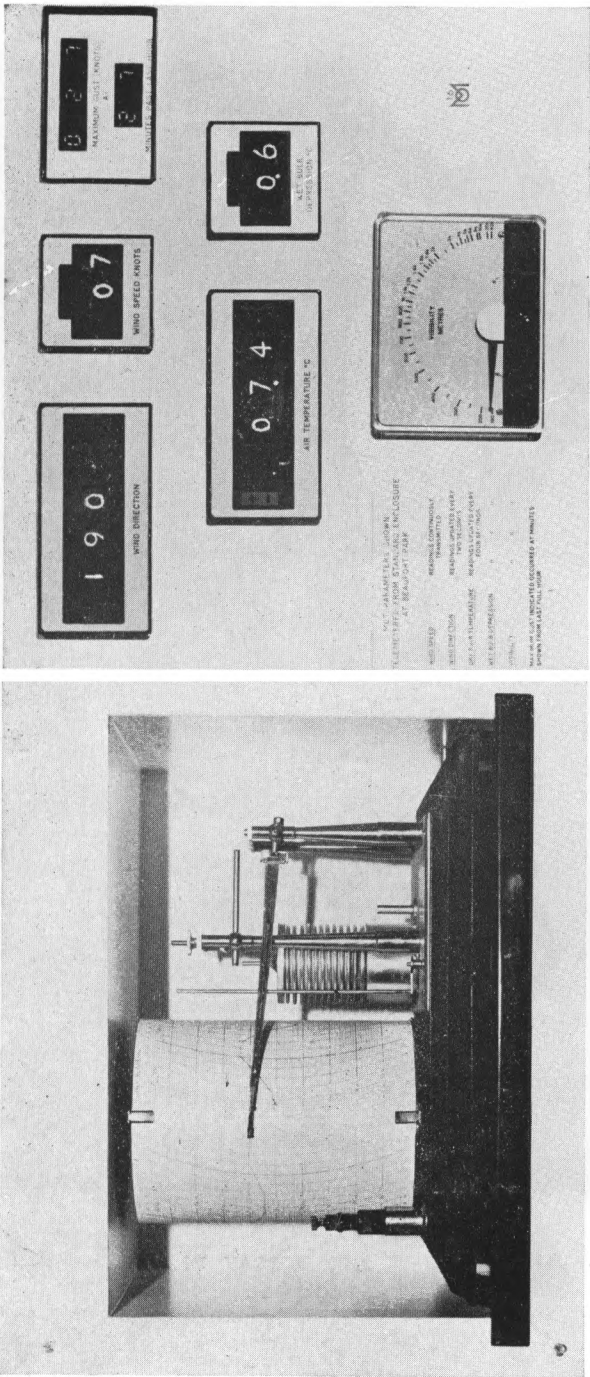


PLATE IV—DISPLAY IN ENTRANCE HALL AT METEOROLOGICAL OFFICE HEADQUARTERS, BRACKNELL

See page 74.

Air temperature is measured by an electrical resistance thermometer³ in a Kelvin bridge; the resulting signal is converted by an operational amplifier to give an output of 0–10 volts for the range -20°C to $+40^{\circ}\text{C}$.

Wet-bulb depression is measured by two electrical resistance thermometers in a comparison bridge; the resulting signal is converted by an operational amplifier to give an output of 0–10 volts for the range 0–12 degC.

The output from the transmissometer, in the range 0–10 volts, is fed to a smoothing circuit to remove rapid fluctuations of signal and then to an operational amplifier.

The multiplexer is an electronic 16-way switch which is controlled by an address counter. Pulses at one-second intervals from the Telecode unit are combined into a 4-bit address code which is used to switch the input signals, to identify the channel being transmitted and to synchronize the operation of the analogue-to-digital converter. The input channels in the multiplexer are interconnected to give wind direction at 2-second intervals, and temperature, wet-bulb depression and visibility at 8-second intervals. Two reference voltages are also fed to the multiplexer, one at 0 volts, the other at 9 volts; these are transmitted at 16-second intervals.

The analogue voltages are converted into 10-bit binary words by the analogue-to-digital converter and combined, in the Telecode unit, with the appropriate 4-bit address code to form serial words of 16 bits in length (the extra two bits are sent as zeros). A complete conversion takes approximately one second. The 16-bit word is used to modulate a second Teleshift transmitter working at a centre frequency of 1380 Hz, a binary '0' being 1350 Hz and a binary '1' being 1410 Hz.

The outputs of both Teleshift transmitters are fed continuously into a private Post Office line. In the event of a failure on either transmission channel, a warning light at the receiver will indicate a fault condition. The Post Office line is terminated in the Richardson Wing of Meteorological Office Headquarters.

The data receiver and CFO display. A block diagram of the data receiver is shown in Figure 2. The basic function of the receiving equipment is to re-form the coded signals from the transmitter into analogue voltages. The incoming data signals on the Post Office line are fed to two Teleshift receivers, each tuned to accept signals within a set frequency band. Thus the wind-speed data transmitted on a carrier frequency of 2340 Hz are detected, demodulated and passed to the Teleducer receiver as a signal varying between 5 and 25 Hz. The Teleducer converts this signal into a voltage varying between 0 and 10 volts. An amplifier provides sufficient power to drive the pen-chart recorder which displays the data in CFO and also the meters in the entrance hall display.

The remaining data channels are detected by the 1380-Hz Teleshift receiver and then fed to the Telecode receiver as a series of 16-bit binary words. Each word is held in a multistage shift-register while a circuit checks that the correct number of bits has been received, and is then fed in parallel to the digital-to-analogue converter and address decoder. While the conversion is taking place, the address decoder causes the de-multiplexer to switch its output to the appropriate sample-and-hold circuit where the analogue signal is held until it is updated. The contents of the sample-and-hold circuits are

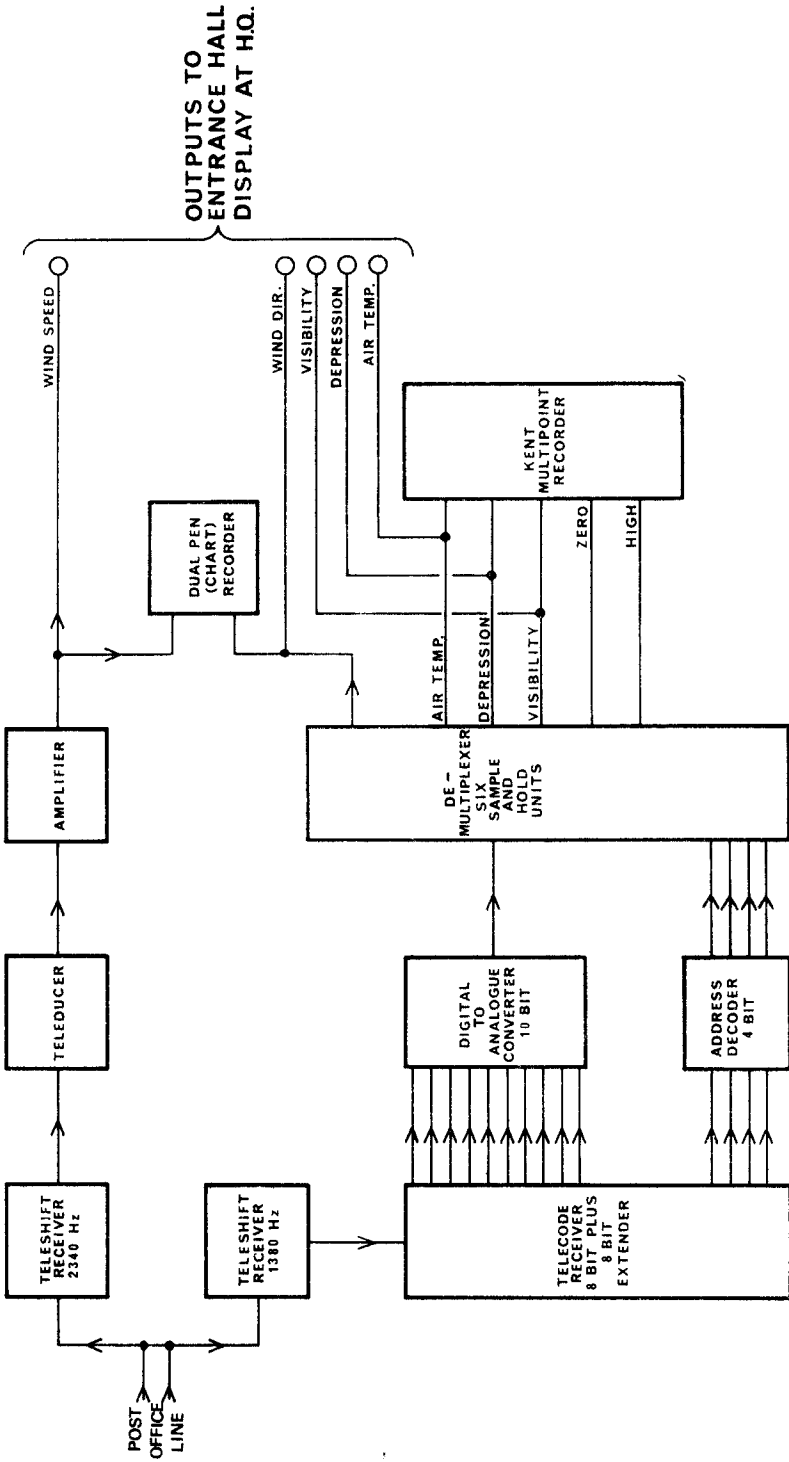


FIGURE 2—CARD DATA RECEIVER

displayed on the wind-direction chart or on the 12-channel recorder in CFO, and also on the entrance hall display. The 12-channel recorder display of air temperature, wet-bulb depression, visibility and the two reference voltages has a different colour for each trace.

The entrance hall display. A block diagram for the Meteorological Office Headquarters entrance hall display is shown in Figure 3. With the exception of visibility, all the displays are by digital panel meters. Data in the form of analogue voltages in the range 0–10 volts are fed from CFO via a multicore cable. The inputs to the digital panel meters are not compatible with these voltages and scale-changing is required as listed in the table below.

Element	Line input volts	Range covered	Meter input	Range displayed
Wind speed	0–10	0–200 kt	0–2 V	0–199 kt
Wind direction	0–10	90°–630°	0–180 mV	0–360°
Air temperature	0–10	–20° to +40°C	0–300 mV*	–20° to +40°C
Wet-bulb depression	0–10	0–12 degC	0–1·2 V	0–12 degC
Visibility	0–10	100 m–40 km	0–10 mA†	100 m–40 km

* An offset voltage is provided to give negative readings when required.

† An analogue meter is used with a series resistor.

The wind-speed scale-changing circuit uses an operational amplifier to change voltage levels and incorporates the facility for producing mean wind speeds if required. This is not used for the entrance hall display.

The wind-direction scaling circuit is more complex since the range of direction covered by the incoming signal is 540°. Operational amplifiers are used with offset and comparator functions to sense when the wind direction passes through north (360°), and to add correcting voltages to the display.

Air-temperature scaling requires a potential-divider network and an offset voltage for negative readings. The wet-bulb depression requires a potential divider only.

The visibility display is by a 0–10-mA analogue meter. The visibility scale is non-linear because the signal relates to transmittivity rather than to meteorological optical range. The display of this element by a digital meter is under consideration, but a sufficiently simple technique has not yet been devised because of the complex form of the transfer function between visibility and sensor signal.

The presentation of the maximum gust and the times of occurrence uses techniques developed for the Digital Anemograph Logging Equipment (DALE). The wind-speed data are fed to an 'upcount' analogue-to-digital converter. This device stores the maximum value presented to it in digital form and will only update when the previous maximum value is exceeded. When updating occurs, a pulse is produced which allows the time display to update also. A crystal clock provides one-minute pulses into the time store. The time store resets to zero at a count of 60 and at the same time resets the upcount analogue-to-digital converter to zero. The maximum gust value in the store is displayed, along with the time of its occurrence.

The digital indicators may give an impression that the data are being sampled at a greater rate than is actually occurring; this is due to the digital meter scanning the output of the sample-and-hold circuits approximately once per second.

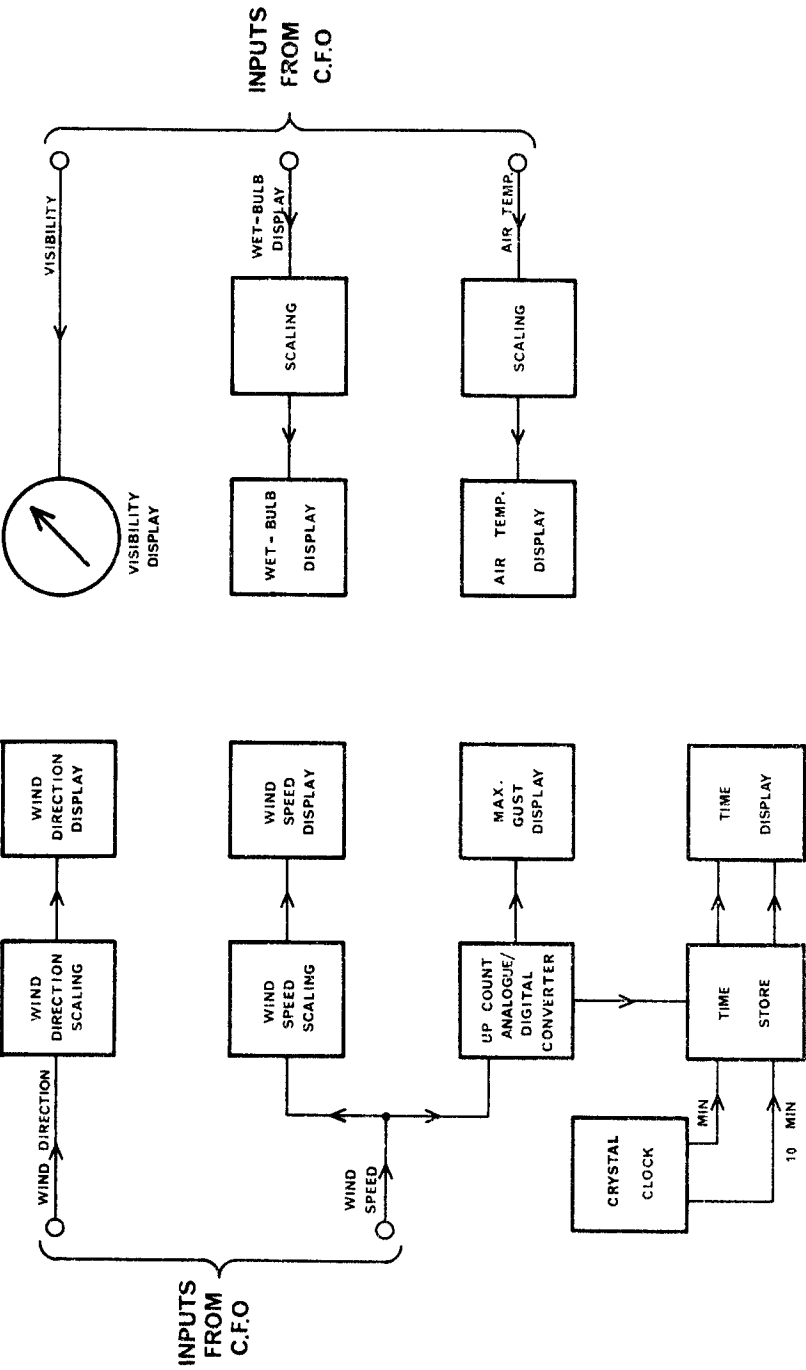


FIGURE 3—ENTRANCE HALL DISPLAY AT METEOROLOGICAL OFFICE HEAD-QUARTERS, BRACKNELL

Other applications. The CARD equipment, described in an earlier paragraph, can handle up to 16 analogue channels of information. It can, however, be expanded to accommodate up to 64 channels. The normal rate of transmission is one channel per second. By increasing the bandwidth of the system and using high-speed Telecode and Teleshift, a channel rate of six per second is possible.

The transmitted data may be processed in several ways :

- (a) Mean values can be calculated and displayed.
- (b) As is shown in the entrance hall display, maximum values can be stored and updated when necessary.
- (c) It is also possible to provide a print-out of data or to feed the output direct into a computer.

Several receivers may be run from one transmitter in order to provide displays at widely separated locations. In such an arrangement, each receiver would be linked to the transmitter by a single telephone line.

CARD has obvious applications on airfields where sensors may have to be remote from the observing office, and where runways and taxi-tracks may make the laying of multicore cables difficult and expensive. CARD merely requires a single telephone cable which may be as long and as indirect as circumstances require. It would also be a simple matter to switch the output from a transmitter to a distant collecting station when an airfield was closed.

The next application of CARD is to be between the Post Office Tower in London and London Weather Centre. Readings taken from sensors measuring wind speed and direction, air temperature, humidity and sunshine high up on the tower, will be displayed and recorded in the forecast room of the Weather Centre.

CARD provides the user with facilities which in some respects are similar to those provided by the Mk II Meteorological Office Weather Observing System (MOWOS). Although the latter is only interrogated when data are required, the structure of Post Office line-rental charges and the relative capital costs of the two systems are such that it could be more economical to use CARD over short distances (say, less than about 30 miles). On the other hand, MOWOS has the advantage that any remote station can be interrogated by any station equipped with the necessary receiving equipment.

The present CARD system requires a 240-volt mains supply but the circuits could be further developed for operation from batteries if necessary.

Acknowledgement. The help and advice of Mr C. V. Else, who initiated the project, is gratefully acknowledged.

REFERENCES

1. ELSE, C. V.; The Meteorological Office Mk V wind system. Submitted to the *Meteorological Magazine*, London.
2. London, Meteorological Office. Handbook of meteorological instruments, Part I. London, HMSO, 1962, Chapter 5.
3. London, British Standards Institution. British Standard 1904:1964. Industrial platinum resistance thermometer elements. London, 1964.

THE DETERMINATION OF LARGE-SCALE VERTICAL MOTION BY A MODIFIED ISENTROPIC TECHNIQUE

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Summary. A modified technique for the determination of vertical motion by isentropic analysis is described which takes account of the diabatic effect of radiative cooling of the atmosphere. The method is applied to a case study of anticyclonic conditions and the computed vertical motion is shown to be consistent with the synoptic changes; little variation with height is evident for some distance above the top of the boundary layer. Limitations of the method are discussed.

Introduction. During recent studies of the convective boundary layer over land¹ it has become evident that an essential part of boundary-layer budgeting is the determination of the large-scale vertical motion $\bar{\omega}$ at the top of the layer. This is particularly important for the computation of the rates of entrainment into the layer of heat, moisture and mass from the 'free atmosphere' above. In a more general context, however, the problem of obtaining $\bar{\omega}$ can be considered as part of the more basic meteorological problem of the construction of air trajectories within the atmosphere. Because of the quasi-isentropic nature of air motion above the convective boundary layer, airflow in surfaces of constant potential temperature gives useful approximations and analyses of air motion in such surfaces have been used by many authors (e.g. Green *et alii*² and Danielsen³) in estimating trajectories. However, limitations to the approach can be expected to arise from the presence of non-adiabatic processes operating within the atmosphere as well as from intrinsic errors in the reported data. Of the non-adiabatic processes, the most important are turbulent mixing in the boundary layer, moist convection and long-wave radiative cooling. Others such as adjustments following Kelvin-Helmholtz instability may only rarely be significant. Above the boundary layer and away from regions of moist convection, the principal diabatic process is long-wave radiative cooling which leads to motion through isentropic surfaces towards lower potential temperature; in the following note we incorporate the effect of long-wave radiative cooling into an isentropic approach in the context of obtaining a representative value of large-scale vertical motion appropriate to a level just above the boundary layer by using routine synoptic data. The technique proves particularly suitable when lapse rates are small, as is often found for some distance above the inversion which frequently marks the convective boundary-layer top.

Isentropic analysis. The basic technique employed in isentropic analysis is to draw streamline and isotach patterns in a chosen surface of constant potential temperature, θ_1 , at successive observation times t , $t + \Delta t$, $t + 2\Delta t \dots$ by using observations of wind speed and direction at each station in the radiosonde network. From such a sequence of charts an isentropic trajectory can be inferred, assuming that the time interval Δt is short enough for the streamlines to be taken as trajectories during this period, i.e. that the field of motion is adequately described by charts Δt apart. The vertical

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motion of the air along the trajectory between two successive times, $t, t + \Delta t$ is then given by the change in the level of the parcel on the isentropic surface, i.e. by

$$[p(\theta_1, t + \Delta t) - p(\theta_1, t)] \text{ (following parcel).}$$

The assumption that the air remains in the surface neglects the presence of long-wave radiative cooling and a more realistic estimate of parcel trajectories, and hence of vertical motion, can be made by including its effect. If the radiative cooling of air in the time Δt is $\Delta\theta_R$ at the level of interest, then we modify the above approach and follow air for the first half of the interval Δt on the chosen isentropic surface θ_1 plotted for time t , and for the second half of the interval on the isentropic surface $\theta_1 - \Delta\theta_R$ for time $t + \Delta t$. The average vertical motion of the parcel during this time along the estimated trajectory is, in this case, given by

$$\bar{\omega}\Delta t = \frac{\overline{Dp}}{Dt} \Delta t = [p(\theta_1 - \Delta\theta_R, t + \Delta t) - p(\theta_1, t)] \text{ (following parcel).}$$

This procedure is shown schematically in Figure 1.

As mentioned above, the value of $\bar{\omega}$ obtained is a mean value for a *parcel*. In practice, it is often desirable to obtain values of $\bar{\omega}$ representative of some selected location P and we have here adopted the convention of ascribing the value of $\bar{\omega}$ to a position of the parcel in space midway between chart times. In practice this differs little from its mean position along the trajectory and simplifies the analysis, since the starting level $p(\theta_1, t)$ of the parcel can be simply located by backwards projection from P on the θ_1 chart over a distance equivalent to a time of travel $\Delta t/2$ whilst forwards projection from P on the $\theta_1 - \Delta\theta_R$ chart gives the finishing level $p(\theta_1 - \Delta\theta_R, t + \Delta t)$ and hence $\bar{\omega}$.

For practical application Δt is taken to be 12 hours, the interval between available radiosonde information. Typically in our studies, the length of a 12-hour trajectory is about 150 km and the end-points lie well within the British radiosonde network. However, the open nature of this network means that little smoothing can be applied in constructing the isentropic pressure-height and wind fields, with the result that any erroneous or unrepresentative sounding is likely to affect strongly the inferred value of $\bar{\omega}$. Figure 2 illustrates the errors in determining the pressure-height as a function of the lapse rate through a layer (within which the lapse rate is assumed constant) arising from a likely error of 0.5 degC in the temperature at all levels. Note that the errors increase with increase of lapse rate, becoming intolerably large as the lapse rate approaches the dry adiabatic. If we further reasonably assume that wind directions may be in error by $\pm 10^\circ$ and wind speeds by ± 2 m/s then by reference to typical isentropic charts, we can infer that an error of ± 10 mb (12 h) $^{-1}$ may arise from a likely error in the trajectories. Combining this with an error of ± 10 mb (12 h) $^{-1}$ typical for a lapse rate through the lower troposphere (cf. Figures 2 and 3 below) suggests that the total probable error in $\bar{\omega}$ is likely to be of the order of ± 15 mb (12 h) $^{-1}$ (root-mean-square

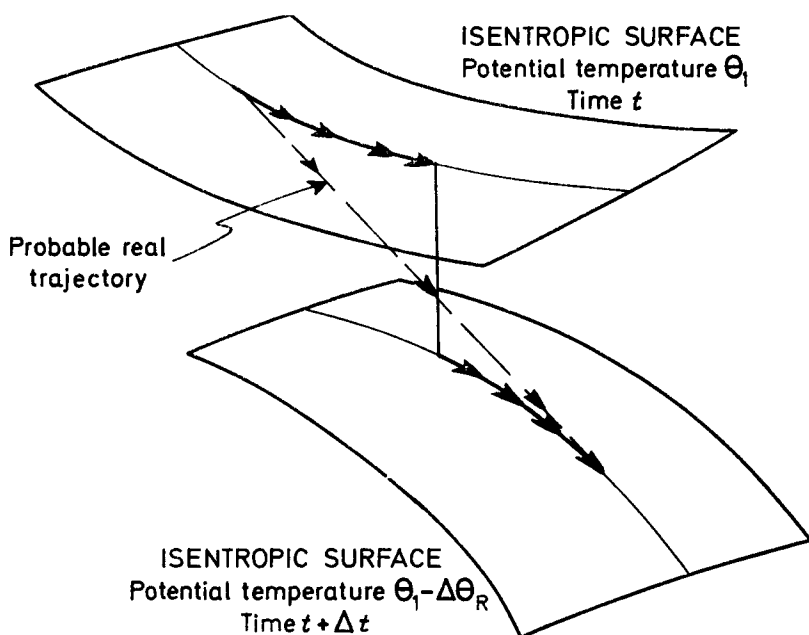


FIGURE 1—A SCHEMATIC REPRESENTATION OF THE METHOD OF DETERMINING THE AVERAGE VERTICAL MOTION OF A PARCEL

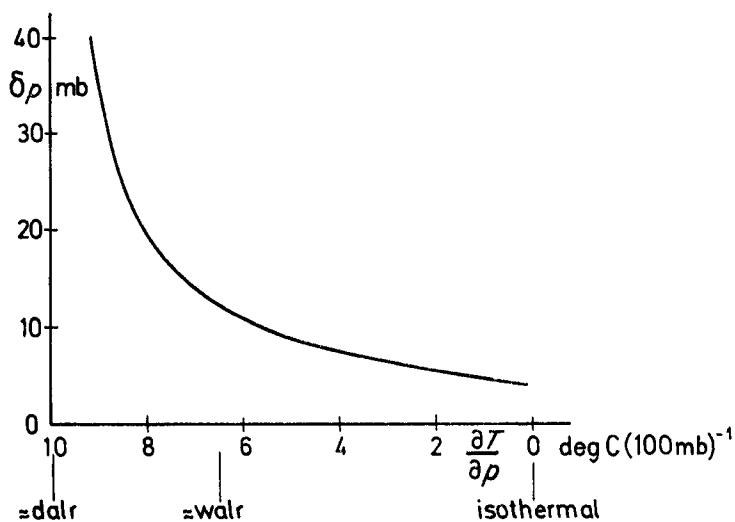


FIGURE 2—THE ERROR IN PRESSURE-HEIGHT (δp) OF AN ISENTROPIC SURFACE AS A FUNCTION OF LAPSE RATE ($\partial T / \partial p$) FOR AN ERROR IN THE TEMPERATURE SOUNDING OF 0.5 deg C

Dry and wet adiabatic lapse rates (dalr, walr) are indicated.

combination). Whilst not insignificant, as shown below such an error is still smaller than the correction which must be applied to take account of radiative cooling.

An application of the method. We applied the technique outlined above to an occasion of settled anticyclonic conditions over the British Isles and initially determined the vertical motion a little way above the top of the boundary layer. The period chosen for analysis was 3–8 September 1971, routine significant-level data from the British network of radiosonde stations being used throughout. Figure 3 shows a sounding typical of the period, with the top of the boundary layer at 840 mb.

By using an Elsasser radiation chart,* the cooling rate of the lowest layer of the free atmosphere through a depth of 100 mb was estimated as 2 degC/day with day-to-day variations an order of magnitude smaller than this and so considered negligible. Consequently, for our analysis with $\Delta t = 12$ hours, we have taken $\Delta\theta_R$ to be 1 degC throughout.

In Figure 4 we show time sequences of the computed vertical motion at 12-hourly intervals at two locations in the south of the British Isles: Silwood Park (Ascot) and a place in the Bristol Channel, together with the pattern of vertical motion at Silwood Park computed without allowance for radiative cooling. The potential temperatures used in the computation were chosen to lie just above the inversion at the top of the boundary layer and so the air is not affected by convection. As an anticyclone intensified over England on the 4th the figure shows descent to take place at both locations, continuing until the 7th when the anticyclone moved away north-eastwards to Scandinavia. Note that trends are shown to occur earlier at the more westward location; descent begins earlier there on the 4th and also weakens there earlier between the 6th and 7th. The maximum rate of descent is about 40 mb (12 h)⁻¹ (≈ 1 cm/s). The form of the time sequences of vertical motion computed with and without allowance for radiative cooling are predictably similar, but values for subsidence rates are smaller by about 20 mb (12 h)⁻¹ when radiative cooling is not included; indeed the implied direction of the vertical motion may even be upwards rather than downwards. The size of the difference depends primarily on the lapse rate in the layer.

We illustrate the variation of mean vertical motion with height by choosing a second (higher) potential temperature, appropriate to approximately the 650-mb level, and applying the method as before. Figure 5 compares the mean vertical motion at Silwood Park at this higher level with that at the lower level (about 800 mb) already displayed in Figure 4. The pattern of vertical motion is similar at both levels, but on the 4th the results indicate that descent begins first at the upper level. Thereafter there is descent at both levels until the 7th. During the period of descent, there appears to be little variation of $\bar{\omega}$ with height for some distance above the boundary-layer top. However, there is a suggestion of greater variability at the upper level, probably as a result of greater errors incurred with generally steeper lapse rates aloft (cf. Figure 3).

* A chart which, by providing a graphical method of numerical integration of the equations of radiative transfer in the atmosphere, permits of the calculation of the upward and the downward fluxes of radiation at any level, the vertical distribution of temperature and humidity being known.

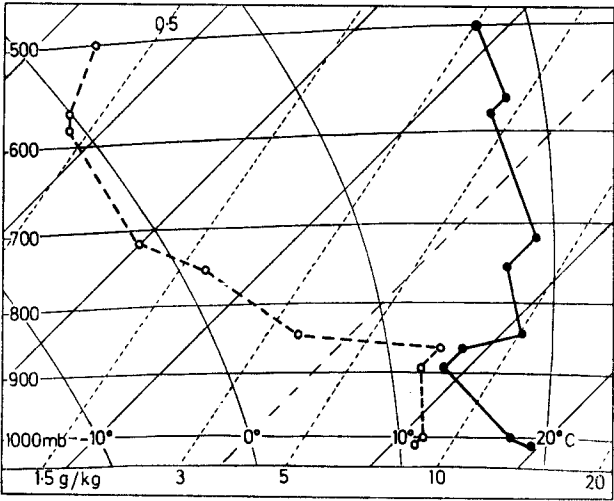


FIGURE 3—CRAWLEY RADIOSONDE SOUNDING, 12 GMT, 5 SEPTEMBER 1971
●—● Dry-bulb temperature ○—○ Dew-point temperature
The sounding is typical of subsidence conditions.

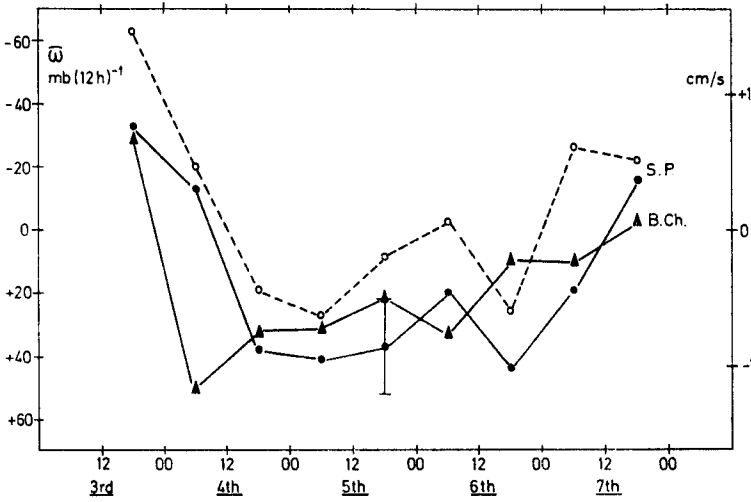


FIGURE 4—THE COMPUTED VERTICAL MOTION ($\bar{w}$) JUST ABOVE THE BOUNDARY-LAYER INVERSION, 3-8 SEPTEMBER 1971
▲—▲ Bristol Channel ●—● Silwood Park, Ascot
○—○ Silwood Park, without allowance for radiative cooling

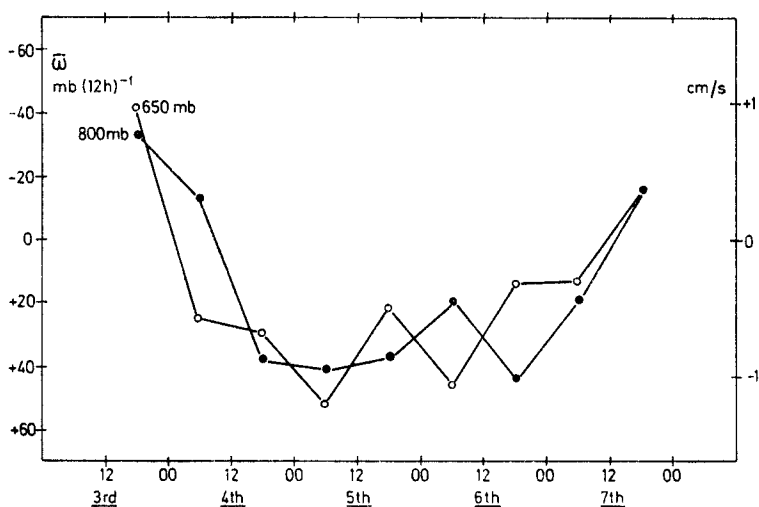


FIGURE 5—THE VERTICAL MOTION ($\bar{\omega}$) AT SILWOOD PARK, 3-8 SEPTEMBER 1971

- — ● $\bar{\omega}$ just above the boundary layer (approximately 800-mb level)
- — ○ $\bar{\omega}$ at approximately 650 mb

Large-scale vertical motion over a short period. The shortest period over which a value of $\bar{\omega}$ can be determined using routinely obtained radiosonde data is 12 hours. To consider the applicability of such a value to periods shorter than this we have examined sequential radiosonde observations made approximately hourly at Silwood Park on a day when warming through the first 200 mb or so above the boundary layer due to horizontal advection was negligible (as deduced from the upper-air synoptic network), and compared the observed changes in the temperature profiles with time with those expected using the 12-hour mean value of $\bar{\omega}$, due allowance being made for radiative cooling. The computation of $\bar{\omega}$ was made independently of the Silwood Park data. The sequential soundings show a definite trend, temperatures increasing at all levels through the day (implying subsidence), which can be broadly accounted for by the mean vertical motion. Figure 6 shows a typical comparison of measured and predicted changes, in this case between radiosondes launched 5 hours apart (1130 GMT and 1646 GMT respectively). The predicted and observed profiles for the 1646 GMT radiosonde are generally in good agreement; the largest difference of about 1 degC occurs around the 750-mb level where the observed temperature increase is 3 degC and the predicted value is 2 degC. These differences between observed and predicted warming do not vary systematically with height over the period of sequential soundings as a whole and so cannot be accounted for by a steady change with height of the 12-hourly mean vertical motion. They may, in part, be attributed to measurement errors between successive radiosondes; otherwise we must infer either variations in $\bar{\omega}$ or differential horizontal advection over these levels on time and space scales considerably

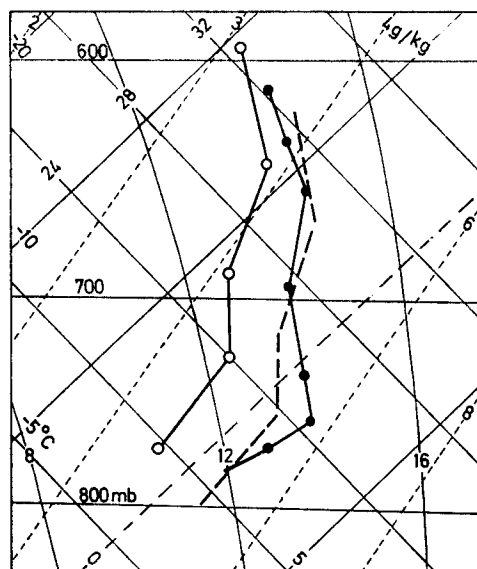


FIGURE 6—COMPARISON OF OBSERVED AND INFERRED PROFILES

Two soundings made at Silwood Park on 16 June 1972 are shown by continuous lines: 1130 GMT (○ — ○) and 1646 GMT (● — ●). The pecked line shows a sounding appropriate to the later time inferred from the first sounding and using the mean value of the vertical motion computed for Silwood Park.

smaller than that of the synoptic network (or, additionally, small variations may also arise from associated variable cooling rates if the moisture content is particularly non-uniform — not observed on this occasion). They are, however, on average only about 20 per cent of the large-scale trend, so that on this occasion it appears that variations on time scales less than 12 hours were relatively small and diurnal variations can be considered unimportant, changes in the value of $\bar{\omega}$ being primarily on the synoptic time scale.

Concluding remarks. It is evident that the diabatic process of radiative cooling should not be neglected in estimating trajectories and the associated mean vertical motions. Although expected errors in the technique as described are not likely to be small, the internal consistency between time sequences of vertical motion at different locations gives confidence in the method, strengthened by systematic day-to-day changes in the patterns of the isentropic charts. This, together with our consideration of hourly sequential radiosonde observations, further suggests that variations of $\bar{\omega}$ are primarily on the synoptic scale. As we have indicated, however, a severe limitation in the method exists where the lapse rate of temperature approaches the dry adiabatic, it being most suitable for application in more stable layers.

Acknowledgement. This work was carried out under a Natural Environment Research Council research contract for studies of the convective boundary layer over land.

REFERENCES

1. CATTLE, H. and WESTON, K. J.; The structure and development of the boundary layer over land. (Talk given at the Royal Meteorological Society Discussion Meeting on 'Recent research in the U.K. on the atmospheric boundary layer and air/sea interaction' on 16 May 1973; a summary appears on pp. 767-768 of the October 1973 issue of the *Quarterly Journal of the Royal Meteorological Society*, London.)
2. GREEN, J. S. A., LUDLAM, F. H. and MCILVEEN, J. F. R.; Isentropic relative-flow analysis and the parcel theory. *Q J R Met Soc, London*, 92, 1966, pp. 210-219.
3. DANIELSEN, E. F.; Trajectories: isobaric, isentropic and actual. *J Met, Lancaster, Pa*, 18, 1961, pp. 479-486.

REVIEWS

Air pollution and atmospheric diffusion, edited by M. E. Berlyand (translated by the Israel Program for Scientific Translations, Jerusalem). 240 mm × 165 mm, pp. v + 220, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1973. Price: £7.00.

Although an up-to-date appraisal of Russian contributions in atmospheric and oceanic physics is well provided for in the regular translations organized by the American Geophysical Union, the developments in the practical contexts of air pollution are not so readily accessible. Even at the recent IUTAM-IUGG Symposium on Turbulent Diffusion in Environmental Pollution (Charlottesville, U.S.A., 8-14 April 1973), there were no contributions in these particular contexts. It is useful therefore to have this collection of translated papers from the Israel Program for Scientific Translations.

Mr Berlyand is a leading figure in the practice of air pollution meteorology in the U.S.S.R., who has already provided several survey papers in translated form, including an extensive appendix in W.M.O. *Technical Note* No. 121, and the present volume of which he is editor now provides an opportunity of studying various individual papers on work of the last few years. There are 19 altogether, of which seven are concerned with diffusion theory and observational studies of dispersion, five with various relevant aspects of boundary layer structure and the remainder with methods of sampling and analysis of pollutants.

The opening paper, by Berlyand and Onikul, is by far the most extensive of the collection and cites a long list of references, largely of the work of Berlyand and various co-authors. Many of the references are to reports in the G.G.O. (Main Geophysical Observatory) series available in original form in the Meteorological Office Library. This particular paper quotes the formulae used in practice for estimating concentrations of pollution from power stations and industrial emissions. It has been evident for some time that the Russian workers favour a rather formal approach, and the basis for the formulae referred to lies in solutions of the classical three-dimensional equation of diffusion, incorporating vertical and lateral eddy diffusivities and an arbitrary speed of sedimentation for particles of pollution.

It is interesting to note that some progress is claimed to have been made for the very important practical case of near-calm conditions, though the reader will need to seek out other references for further details of this work. Also, for the case of a power-station plume it is noteworthy that the Russian

treatments include the familiar simple representation of the opposing effects of wind speed on plume rise and dilution, prescribing a 'most dangerous wind speed' at which the ground-level concentration is a maximum. In the recent power-station studies in England this simple result has not been confirmed and indeed a much more complex variation with wind speed has been observed, showing high values of the maximum (with respect to distance from the source) for light winds by day and also for strong winds by day or night. The Russian calculation of a 'dangerous velocity' is claimed to be supported by observations reported (on p. 92) in one of the shorter papers in this collection. However, these observations contain so much scatter that it is difficult to see how it has been possible for any conclusion to be drawn about a systematic variation with wind speed.

The foregoing are examples of attitudes and results which are somewhat surprising on first encounter and it is fairly obvious that a realistic appraisal of the Russian work in this field will require close study, not only of the present papers but also of the various papers which are cited in support.

F. PASQUILL

The world in figures, by Victor Showers. 260 mm × 175 mm, pp. xii + 585, illus., John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1973. Price: £6.50.

What a task the author undertook in compiling this book of nearly 600 pages, mainly of numbers, giving geographical, physical and demographic statistics for the world, for while some of his material is the hard rock of fact, such as the heights of mountains, other material is as shifting sand, as political divisions alter and populations grow! To bring the updated task to a successful conclusion in November 1972 and achieve publication in less than a year is more than creditable.

Clearly the author had to make a choice of the subjects he would include and he has wisely aimed at those whose numerical values are not likely to change rapidly, either by revision or by development. He has chosen to cover three aspects of the world, namely the numerical aspects of the physical features, the population statistics and climatic statistics where available. The first of these is dealt with in more detail than is commonly found in gazetteers, atlases or reference books and there are extensive tables of the largest seas, longest rivers, highest mountains, and so on. The population statistics are given country by country and city by city along with historical information for each of the more than 1600 cities.

The climatic data give for each city the latitude and longitude, the period of the meteorological records from which the data were extracted, the mean yearly temperature, the means for the warmest and coldest named months, the absolute maximum and minimum temperatures, the annual mean maximum and minimum temperatures and the mean annual rainfall; the statistics for extreme temperatures and for rainfall may be drawn from longer-period records than are used for the mean temperatures. The entry also gives an elevation which is 'that of the city centre or principal business district or an average of elevations at several points of the city: otherwise it is that of the meteorological station'. The bibliography gives the sources for

the information and some comparisons with the sources show that the transcription and proof-reading have been excellent. A surprising feature is that the climatological tables are given *twice*, once in feet, inches and on the Fahrenheit scale and again in metres, millimetres and on the Celsius scale: it is difficult to believe that this is necessary and if desirable that the most economic method of presentation has been used. Meteorologists may well wonder what use can be made of these restricted data, since almost all climatological inquiries ask for more data than are given here, and so be led to wonder whether demographers too find that the data with which they are familiar are too scantily reproduced.

From its very nature the book is not aimed at a well-defined group of readers; it is essentially a reference book and will find its way into libraries rather than on to personal bookshelves.

E. KNIGHTING

OFFICIAL PUBLICATIONS

The following publications have recently been issued:

Geophysical Memoirs

No. 118. Northern hemisphere monthly and annual mean-sea-level pressure distribution for 1951-66, and changes of pressure and temperature compared with those of 1900-39. By H. H. Lamb, M.A., P. Collison, B.Sc. and R. A. S. Ratcliffe, M.A. (London, HMSO. Price: £2.60.)

This publication is intended to draw attention to the small but significant changes that have taken place in the atmospheric circulation of the northern hemisphere and in the mean temperature over much of Europe since the early part of the 20th century.

Changes in the level of monthly average temperature over much of Europe reflect the pressure changes; there is clear evidence that winters (particularly January and February) have been colder in the more recent period and there are smaller but interesting changes in other months.

No. 119. A climatology of the stratosphere over north-west Europe. By R. A. Hamilton, O.B.E., M.A., F.R.S.E., B.D. Mason, B.Sc. and G.C. Bridge. (London, HMSO. Price: £2.10.)

The results of over 200 meteorological rocket soundings made from West Geirinish, Outer Hebrides, during the period 1964-72 are discussed. Monthly data comprising temperatures and zonal and meridional wind components at various stratospheric levels are statistically analysed. Stratospheric warmings are discussed, and simultaneous temperature and wind data from a three-station network are presented. There is an account of the diurnal variation with due consideration being given to the difficulty of obtaining accurate day-time temperature values because of radiation error.

British Rainfall 1966. (London, HMSO. Price: £10.)

This publication provides a comprehensive summary of the rainfall of 1964 with discussion of both the incidence of rainfall and its variation from place to place, based on data from about 6000 observers. It contains numerous tables, graphs and maps.

The 'general table of rainfall' forms Part I of the volume and contains annual and monthly rainfall totals and the rainfall of the wettest day where daily values are available. Part II discusses the main characteristics of the year and contains sections dealing with monthly, annual and seasonal rainfall, spells of rainfall deficiency and excess, frequency distribution of daily amounts of rainfall, heavy falls on rainfall days and in short periods, also Penman estimates of potential evapotranspiration. Part III contains the annual report of the 'Snow Survey of Great Britain' for the season 1965-66 by R. E. Booth, 'Potential Evapotranspiration Data, 1966' by F. H. W. Green, and 'A study of magnitude, frequency and distribution of intense rainfall in the United Kingdom' by John C. Rodda.

Marine climatological summaries for the Atlantic Ocean east of 50°W and north of 20°N, 1963 and 1966. (London, HMSO. Price: £6.85 (1963) and £6.70 (1966).)

These summaries are part of a series of similar summaries covering the oceans of the world, which are to be published by nine countries, including the United Kingdom, in accordance with an internationally agreed scheme sponsored by the World Meteorological Organization. The summaries for 1964 and 1965 have already been published and it is intended eventually to publish similar summaries for each of the remaining years from 1961 onwards.

The information in the tables relates entirely to observations made aboard ships on passage, or at Ocean Weather Stations, by observers of countries participating in the scheme. The results included in the tables depend upon large numbers of observations, and production of the tables was facilitated by processing the data by means of programs written for the KDF9 computer at the Meteorological Office, Bracknell.

OBITUARY

Sir Robert Watson-Watt, C.B., LL.D., D.Sc., F.R.S.

We regret to learn of the death in his 82nd year on 5 December 1973 of Sir Robert Watson-Watt. He was one of a band of distinguished people who started their careers in the Meteorological Office at about the time of the First World War and who subsequently found fame in other disciplines. Robert Watson-Watt joined the Meteorological Office in 1915 when he was appointed Senior Professional Assistant to C. J. P. Cave to study radio-waves from lightning at South Farnborough, and he became Meteorologist-in-Charge at the Royal Aircraft Establishment in 1917. His formal connection with the Office ceased in 1921 when he became Superintendent, Radio Research Stations, Department of Scientific and Industrial Research, but his interest in meteorology continued through the years and he became President of the Royal Meteorological Society in 1950, the centenary year of the Society.

Sir Robert's enduring work was of course the discovery and development of radio-location, and he was widely known as the 'father of radar'. His career was lustrous and attended by many honours; his work was of signal benefit to mankind.

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NOTICES

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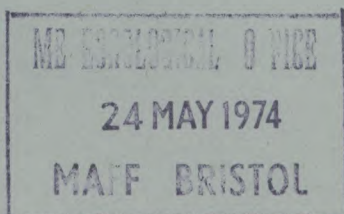
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THE VARIATION OF ANNUAL MEAN SURFACE PRESSURE OVER THE NORTHERN HEMISPHERE DURING THE DOUBLE SUNSPOT CYCLE

By M. K. MILES

Summary. Weighted annual mean surface pressure data over the northern hemisphere for the six sunspot cycles in the present century have been analysed by the method of superposition of epochs. These epochs have been the position of the year relative to sunspot maxima and minima during the three double sunspot cycles made up of cycles 14 plus 15, 16 plus 17, and 18 plus 19. The anomalies from the average for the period 1901-62 were then averaged for each year of the three even solar cycles and each year of the three odd cycles. The only significant difference between the even and odd cycles occurs in the latitude band 20-35°N, where it is found that the average pressure during the even cycles exceeds that during the odd cycles by 0.43 mb, which is significant at about the 1 per cent level. Some of the difference could, however, be due to a secular change.

Introduction. The study was undertaken in an attempt to reproduce a striking result described by Maksimov and Slepcev-Sevlevic.¹ Briefly, they found that around the sunspot maxima of the even sunspot cycles, surface pressure was below average in high latitudes and above average south of 40°N latitude, with the opposite pattern around the maxima of the odd cycles. In addition they found opposite but weaker patterns at the minima of the two cycles, giving thus three maxima and three minima during the double sunspot cycle. These are not, however, equally spaced or of equal amplitude, and the authors do not infer a seven-year cycle. They quote the amplitude of the major difference at high latitudes between the two cycles as about 2½ mb (complete range 5 mb) but do not say if this is taken from the longitudes (Greenland and Alaska) where the effect is strongest, or is a mean round the hemisphere. Since they were using smoothed annual pressures, this value is just about statistically significant even if the maxima had been selected.

Procedure. From the monthly mean surface pressures, stored on magnetic tape, annual mean surface pressures were formed. These were smoothed in the way that the Russian authors had described to give a weighted mean annual pressure P_w related to the unweighted means as follows :

$$P_w = \frac{1}{4} P_{u-1} + \frac{1}{2} P_u + \frac{1}{4} P_{u+1},$$

where P_{u-1} and P_{u+1} are the unweighted values for the year preceding and the year following the year to which P_w refers, and P_u is the unweighted value for that year.

The departures of the smoothed annual means from the average for the period 1901-62 comprising the three double sunspot cycles analysed by the Russian authors were then computed for each grid point from 20°N to 85°N for the northern hemisphere.

The next step was to find the average anomaly for each year of the three even sunspot cycles and each year of the three odd cycles. The designation of each of the years from 1901 to 1962 relative to the sunspot maxima and minima was done according to a paper by Vitinsky² in order to follow the Russian procedure exactly.

The distribution is given in Table I and it will be seen that because the sunspot cycles since 1928 have been about 10 years in length it was thought best to work with 10-year cycles to avoid too much duplication of years. This means of course omitting some years from the period before 1928 when the cycles were longer, but it is thought that the present allocation, if it differs at all from the Russian designation, will affect only one or two years before and after the sunspot minima, and will not in any way affect those around the maxima.

TABLE I(a)—DESIGNATION OF YEARS WITH RESPECT TO SUNSPOT MAXIMUM (X) AND SUNSPOT MINIMUM (N) FOR EVEN SOLAR CYCLES IN THE PERIOD 1901-62

Cycle No.	N	$N+1$	$X-2$	$X-1$	X	$X+1$	$X+2$	$X+3$	$N-2$	$N-1$
14	1901	1902	1904	1905	1906	1907	1908	1909	1911	1912
16	1923	1924	1926	1927	1928	1929	1930	1931	1931	1932
18	1944	1945	1945	1946	1947	1948	1949	1950	1951	1952

TABLE I(b)—DESIGNATION OF YEARS WITH RESPECT TO SUNSPOT MAXIMUM (X) AND SUNSPOT MINIMUM (N) FOR ODD SOLAR CYCLES IN THE PERIOD 1901-62

Cycle No.	N	$N+1$	$X-2$	$X-1$	X	$X+1$	$X+2$	$X+3$	$N-2$	$N-1$
15	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922
17	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942
19	1954	1955	1955	1956	1957	1958	1959	1960	1961	1962

Analysis of results. Figures 1(a) and 1(b) show the distribution of the mean anomalies averaged round several circles of latitude. Each value is a mean of 18 points at 75°N and of 36 points at the other latitudes.

The effect claimed by the Russian authors for high latitudes is not evident in any of the three top curves of Figure 1(a). The curves for latitudes 35° and 45°N, however, show the effect in some degree, though the most pronounced negative anomalies in the odd cycle are centred some three to four years after the sunspot maximum.

None of the anomalies (apart from one for latitude 75°N) approaches the value of 2½ mb quoted by the Russian authors. It may be that this value refers to the locations in Greenland and Alaska where the effects were said to be most marked, so the anomalies for two grid points, one in south-east Greenland and the other in Alaska, were examined. These anomalies are

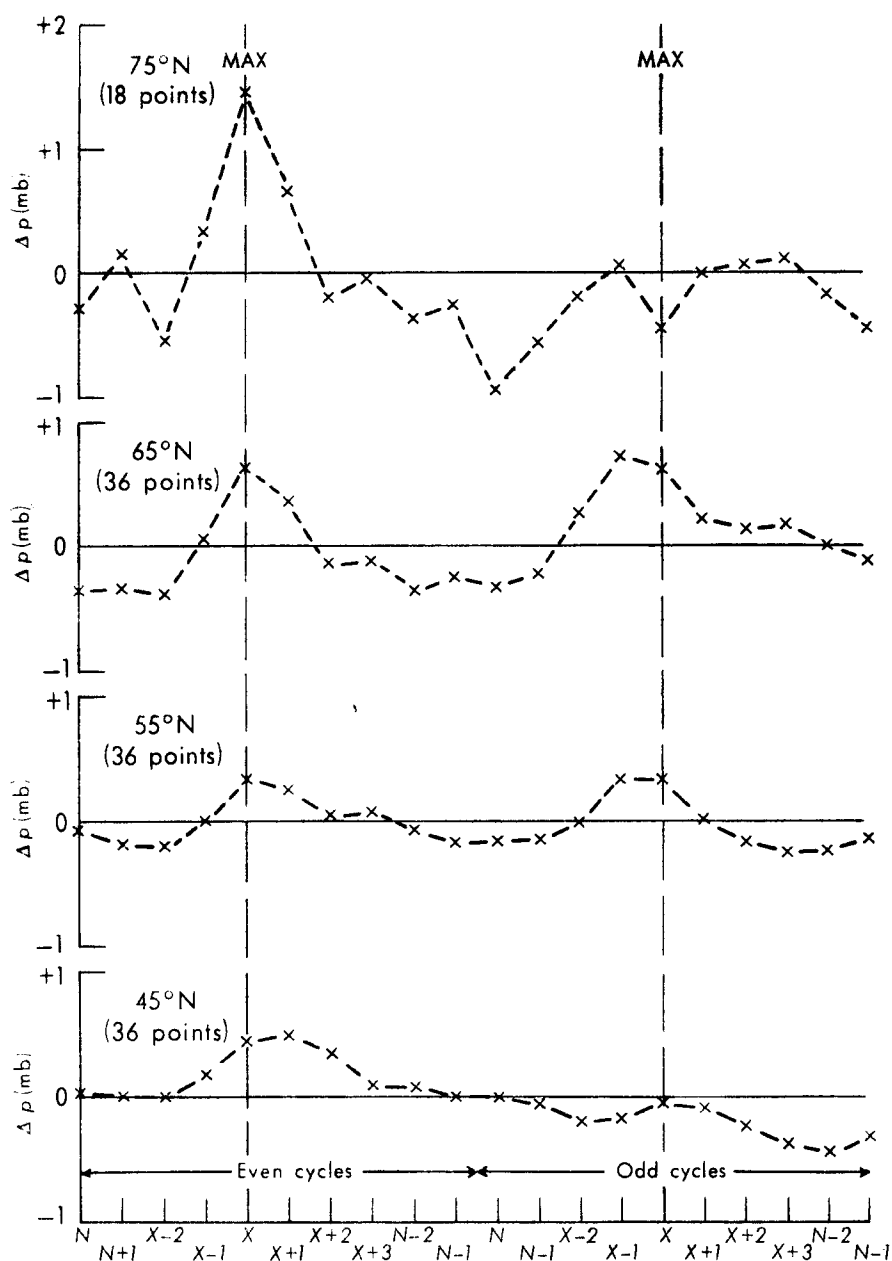


FIGURE 1(a)—AVERAGE ANOMALIES OF WEIGHTED ANNUAL MEAN SURFACE PRESSURE ALONG LATITUDE CIRCLES 45° TO 75°N DURING THREE DOUBLE SUN-SPOT CYCLES (1901-62)

X = year of maximum, $X + 1$ = year of maximum plus one; N = year of minimum, $N + 1$ = year of minimum plus one, etc.

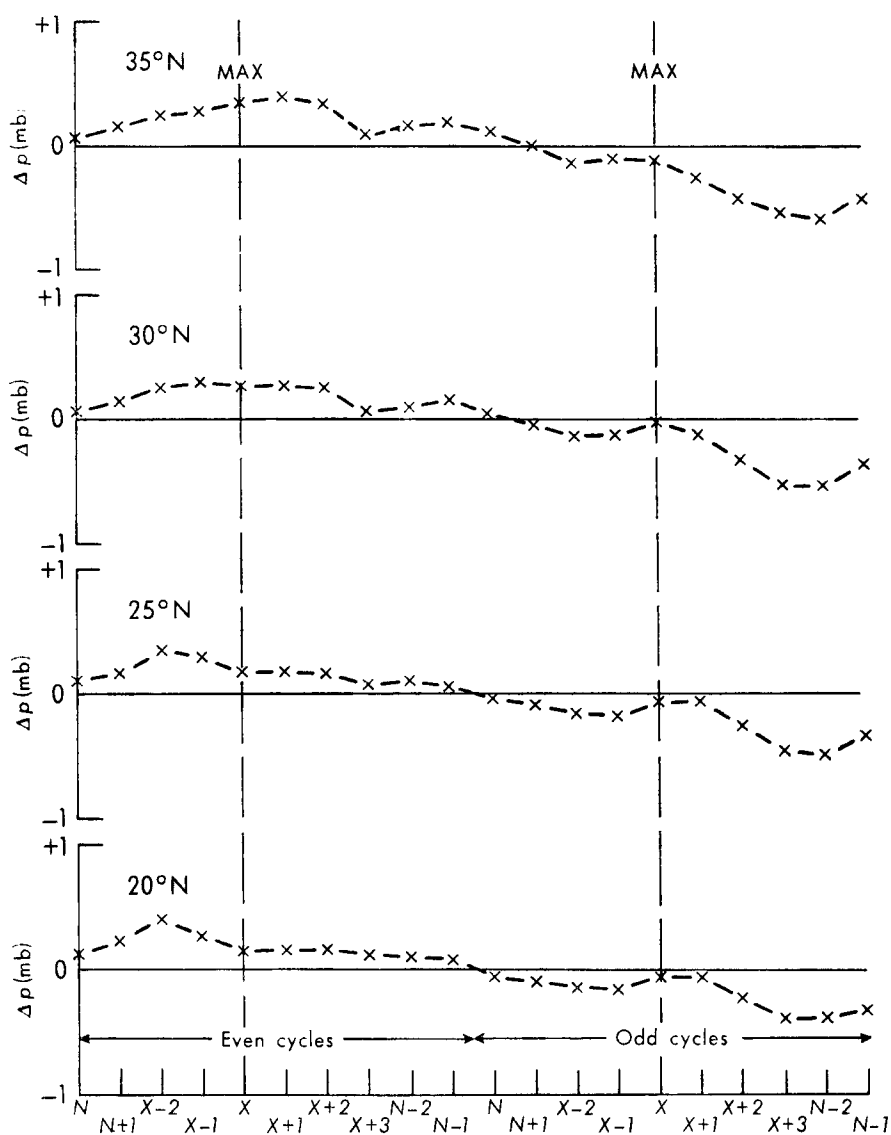


FIGURE 1(b)—AVERAGE ANOMALIES OF WEIGHTED ANNUAL MEAN SURFACE PRESSURE ALONG LATITUDE CIRCLES 20° TO 35°N DURING THREE DOUBLE SUN-SPOT CYCLES (1901-62)

36 points were used in the determination of the mean value for each latitude circle. See note under caption to Figure 1(a).

plotted in Figure 2. For the Greenland position there is some sign of the claimed effect, but for Alaska the pattern is almost reversed as far as the anomalies around the sunspot maxima are concerned. The distribution for a third location — over west Siberia — is also shown. This has so many peaks and troughs that it looks very like a random distribution.

The standard deviations of these weighted annual pressure means are as follows :

65°N 40°W (south-east Greenland) 1.3 mb
65°N 150°W (Alaska) 2.1 mb
65°N 80°E (west Siberia) 1.7 mb.

Each point on the graph is the mean of three years, so these will have standard deviations of 0.8, 1.2 and 1.0 mb respectively. Thus it is possible that any of the anomalies could have been produced by random effects.

To return to the anomalies meaned round the various latitude circles, are any of these clearly outside the value likely to arise from grouping of random data? Assuming that there are four independent values round the latitude circle in high latitudes, increasing to eight in low latitudes, the standard deviations for the mean values plotted in Figures 1(a) and 1(b) range from 0.5 mb in the north to 0.25 mb in the south. Once again, it is possible that all of these anomalies could have arisen by chance.

The distributions at 55° and 65°N suggest a weak effect with a period equal to the single sunspot cycle rather than an effect repeating after a double cycle. The amplitude is, however, insignificantly small, and the apparent regularity of the curve may in part be due to the use of weighted means. The anomalies in the subtropics, though never exceeding twice the standard deviation of the mean, appear to have a surprising amount of organization. The average anomaly for the 10 years of the even cycles is + 0.19 mb and that for the odd cycles is - 0.24 mb, giving a difference which is significant at about the 1 per cent level.

Some of this apparent organization may be due to a secular change in average pressure in the subtropics during the period 1901-62. Data derived from mean maps for 1900-39 and 1951-66 by Lamb, Collison and Ratcliffe,³ show that the average pressure for latitudes 30° and 35°N in the latter period was 0.67 mb lower than in the former period. This in itself is not large enough to explain the difference in the means for the even and odd cycles, but it reduces it to an amount which is within the play of chance. It is planned to carry out an analysis of this sort for several stations in the tropics with surface pressure data going back to 1901 in an attempt to clarify this point.

Conclusion. An analysis of weighted annual mean surface pressures during the double sunspot cycle fails to reveal any unmistakable relation for the three double cycles between 1901 and 1962.

For a location in south-east Greenland there is some sign of an opposite behaviour in even and odd cycles but the magnitude of the effect is so small that it could have arisen by chance. For a location in Alaska the pattern is almost reversed, but again the anomalies could easily have arisen by chance.

For the subtropics there is a rather striking difference between the odd and even cycles, but some of this appears to be attributable to a secular change.

Acknowledgement. Mr S. P. Arnold (a vacation student) wrote the computer program for the extraction of the data on which this paper is based.

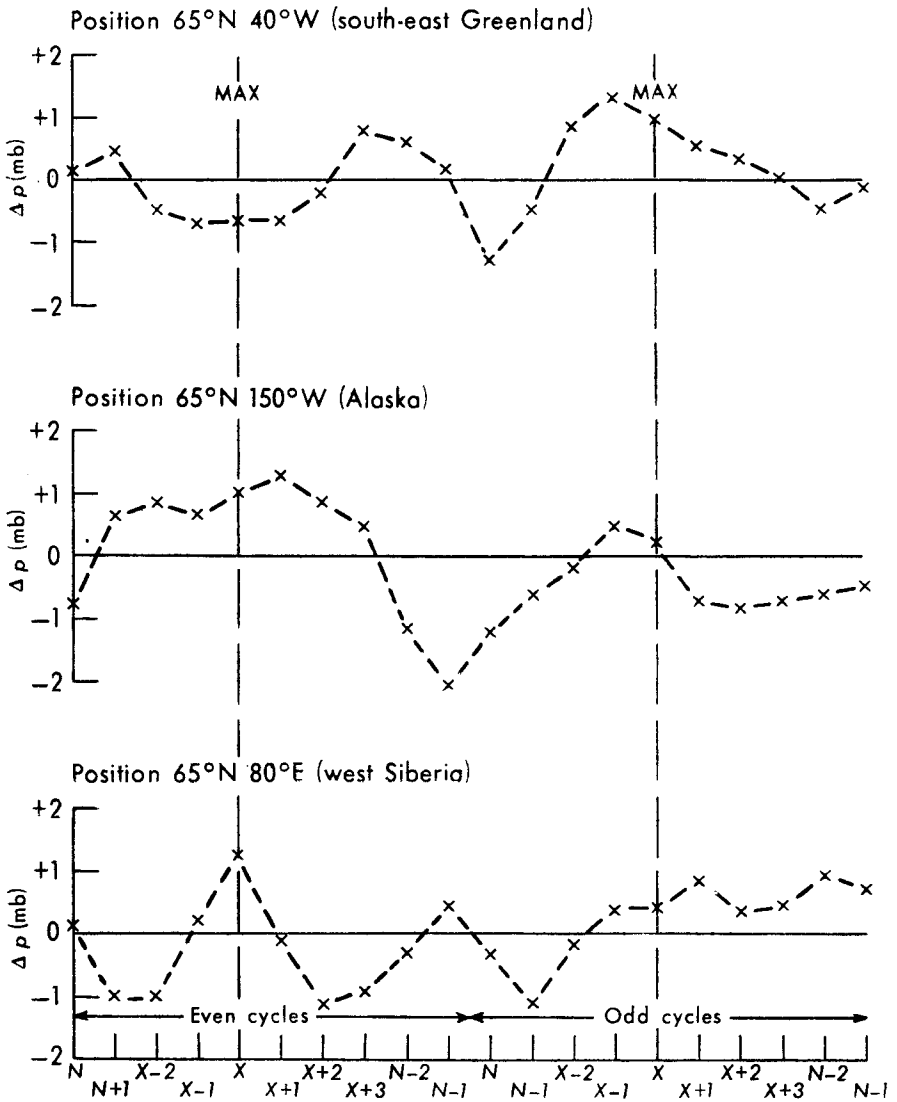


FIGURE 2—ANOMALIES OF WEIGHTED ANNUAL MEAN SURFACE PRESSURE AT THREE LOCATIONS DURING THREE DOUBLE SUNSPOT CYCLES (1901-62)

See note under caption to Figure 1(a).

REFERENCES

1. MAKSIMOV, I. V. and SLEPCOV-SEVLEVIC, B. A.; On the relationship between solar activity and pressure field of the northern hemisphere of the earth. *Doklady Akad Nauk, Moscow*, **201**, 1971, pp. 339-341.
2. VITINSKY, JU. I.; Forecasts of solar activity. Moscow, SSSR Izdat, 1963.
3. LAMB, H. H., COLLISON, P. and RATCLIFFE, R. A. S.; Northern hemisphere monthly and annual mean-sea-level pressure distribution for 1951-66, and changes of pressure and temperature compared with those of 1900-39. *Geophys Mem, London*, **16**, No. 118, 1973.

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A NOTE ON THE OPTIMUM AVERAGING TIME OF WIND REPORTS FOR AVIATION

By R. N. HARDY

Summary. For selected occasions over a three-month period at London/Heathrow Airport, winds averaged over intervals of from 30 seconds to 10 minutes were compared with the 30-second means at later times, simulating the procedure whereby wind observations provided by Air Traffic Control are used by a pilot. The results show that the best averaging time depends on the relative importance of errors of different magnitudes: the few very large errors can be reduced by using a 30-second average, at the expense of many more errors in the range 6-14 kt; the root-mean-square error is normally least with averaging over a period of 5-6 minutes.

Introduction. Pilots need to know the surface wind on take-off and particularly on landing to ensure that the most suitable airspeed is used for the transition. Small eddies of some tens of metres in diameter which may take several seconds to pass an anemometer, affect an aircraft at the most critical times — flare, touch-down and lift-off — for less than one second and are of little consequence. At the other extreme, a mean wind over one hour measured at an anemometer may differ for a large part of that hour from the wind experienced by aircraft, because significant eddies have been smoothed out. Somewhere between these extremes lies an averaging period for surface winds which represents the best possible simple observation from a suitably sited anemometer for use by aviation.

There has not been a great deal of work specifically on this subject. The International Civil Aviation Organization¹ recommends that an airfield surface-wind reading should be averaged over two minutes, until this is shown to be inferior to a different interval. Sparks and Keddle² showed that in a particular synoptic situation, strong westerly winds in a warm sector, a 4-5-minute averaging period was better. This note presents the results of an experiment designed to extend this work, using winds from the Meteorological Office Mk 5 electronic anemometer system at Heathrow and electronic averaging circuits.

Arithmetic averaging applied to a fluctuating signal consists of removing high-frequency oscillations whilst leaving low-frequency components unaltered. The analogy with simple capacitance-resistance (CR) electrical filters has been appreciated for many years. Jones and Pasquill³ have shown how other turbulence statistics may be similarly obtained, while, more recently, Acheson⁴ has discussed in some detail 'exponentially-mapped-post' (EMP) averaging, with particular reference to wind measurement. Kamamoto⁵ carried out experiments using circuits with different time constants and found that the time constant should be from one-half to one-third of the required averaging period.

The Heathrow wind-averaging experiment. An electronic averaging circuit, details of which are given elsewhere,⁶ was connected to the Meteorological Office Mk 5 anemometer system at Heathrow early in May 1973. Thirty-second running means of wind speed and direction were displayed, and values were printed once every 30 seconds when required. To avoid a great deal of uninteresting data, the printer was only operated when the mean wind reached 15 kt, when cumulonimbus cloud or moderate precipitation was reported, or when fronts were forecast in the area. From 3 May to 7 August 1973, the period of operation of the experiment, data were collected for 266 hours; after scrutiny for wind changes, just over 100 hours' data for 42 periods of up to 4 hours each on 27 days were punched on to cards for processing.

An examination of anemogram traces over the same period showed that the averages recorded correspond closely to the variations shown on the charts, and that most of the largest changes had been logged and punched.

Processing. The wind averaged over periods of from 30 seconds to 10 minutes, ending at the same time, was compared with the 30-second average commencing some time later. This delay, or lag, was also varied from 30 seconds to 10 minutes. The averaged wind may be regarded as the 'observation'; the lag corresponds to the interval between the observation and aircraft touch-down; and the later 30-second average was taken to represent the 'actual' wind that an aircraft would have encountered. It is considered that a 30-second run of wind past a stationary anemometer will usually be equivalent to the distance covered in a few seconds of flight, and therefore represents eddy sizes of the correct order for this application.

It may seem that the problem resolves itself into selecting the averaging period which, for normal lags, reduces the root-mean-square (r.m.s.) vector deviation, or 'error', between observed and actual winds to a minimum. This is not necessarily so; Burnham⁷ suggested that a change of wind speed of as little as 10 kt over a period of one or two seconds can in some circumstances be critical on approach, and, whilst he was concerned with gusts rather than changes in the expected mean wind, it is reasonable to assume that errors in the latter of less than 10 kt are of little interest, whilst above this limit they become increasingly important with size. It soon became clear during data-analysis that the averaging period giving the lowest r.m.s. difference rarely coincided with the period producing fewest errors exceeding 10 kt. Because of this, percentages of occasions with errors exceeding 10 kt were also considered, and also how the optimum averaging time varies if this threshold is changed.

Results. Thirty-two sample periods totalling 78 hours and 41 minutes contained differences between observed and actual winds (as defined above) of 10 kt or more with lags of 4 minutes or less, and the results presented here were computed by using these data only. In fact 624 minutes are lost in computing initial means and final lags, so that 68 hours and 17 minutes' data were used.

Root-mean-square errors. Figure 1 shows for each lag the amount, in units of 0.01 kt, by which the r.m.s. error exceeded the minimum r.m.s. value at that lag for each averaging time. It can be seen that if the lag is

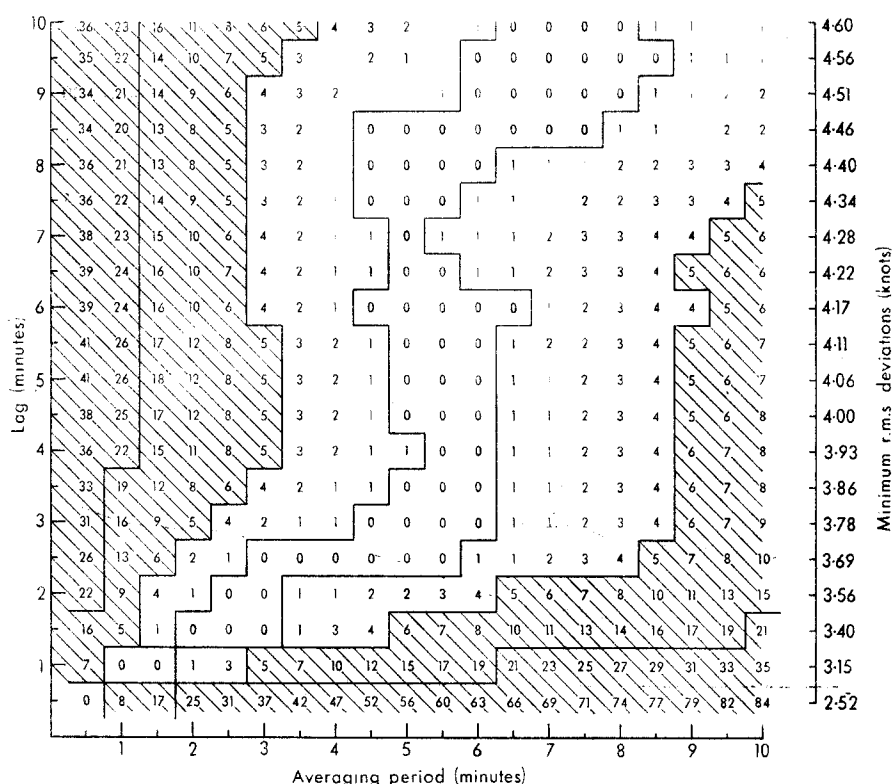


FIGURE 1—AMOUNTS BY WHICH THE ROOT-MEAN-SQUARE VECTOR DIFFERENCES BETWEEN OBSERVED AND ACTUAL WINDS, FOR EACH AVERAGING PERIOD AND LAG, EXCEED THE MINIMUM AT THAT LAG

Values are expressed in units of 0.01 kt, and minima are given at the right-hand side.

likely to be from $1\frac{1}{2}$ to $2\frac{1}{2}$ minutes the best averaging time on this basis is near 3 minutes; if the lag is expected regularly to exceed $2\frac{1}{2}$ minutes then 5-6-minute averaging may be preferable. On the right-hand side of Figure 1 are listed the minimum r.m.s. values at each lag. The change with lag is clearly much greater than with averaging time. In practice anemometers are situated some distance away from the touch-down area and the effective lag, unless the anemometer is directly upwind, will rarely if ever be less than $2\frac{1}{2}$ minutes.

Percentage of differences exceeding 10 kt. Figure 2 presents for lags of from 1 to 10 minutes and all averaging periods the percentage of vector deviations in the sample exceeding 10 kt. It is interesting to see that the number of large errors is, like the r.m.s. deviation, far more sensitive to changes in lag than in averaging time. For all lags, averaging over 5 minutes or more produces more large errors than does 3- $3\frac{1}{2}$ -minute averaging. If the lag is always expected to be 5 minutes or less, there is little to choose between averaging periods in the range $1\frac{1}{2}$ -4 minutes.

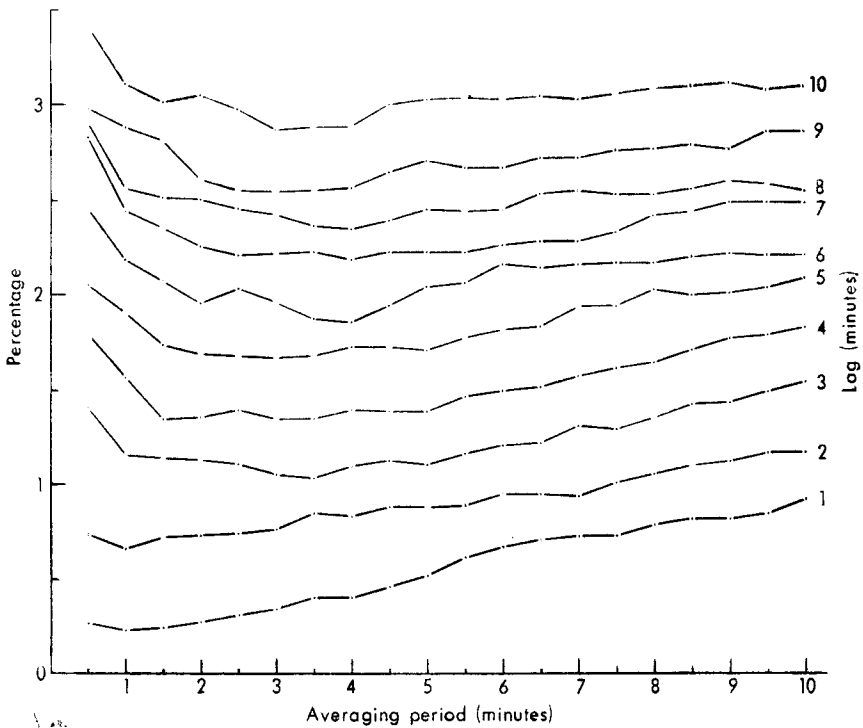


FIGURE 2—PERCENTAGE FREQUENCIES OF VECTOR DIFFERENCES BETWEEN OBSERVED WINDS, AVERAGED OVER PERIODS OF FROM 30 SECONDS TO 10 MINUTES, AND ACTUAL 30-SECOND MEAN WINDS AT LAGS OF FROM 1 TO 10 MINUTES, EXCEEDING 10 KNOTS IN MAGNITUDE

Percentages of differences exceeding various thresholds. Since the cut-off of 10 kt is to some extent arbitrary, Tables I(a) and I(b) have been compiled to show the effect of using different thresholds. Both tables give the total percentage of vector errors of magnitude greater than 2–18 kt, for various averaging times. Table I(a) is for a 5-minute lag, and Table I(b) for a 10-minute lag.

It is quite clear from the minimum values (underlined) that in both cases the small proportion of very large errors is reduced still further if a short averaging time is used, at the expense of a considerable increase in errors between 2 and 12 kt.

Unfortunately the percentages of errors exceeding different thresholds are not directly comparable, because the 68-hour sample was selected to include, as far as possible, all large wind changes over the 98-day period of the experiment. This aim was not completely realized, and it is considered that a better estimate of the overall percentages for summertime in southern England of errors of 10 kt or more, would be one-tenth of those given.

It is interesting to note that the largest vector errors are not associated with periods of strong mean winds but rather with sudden changes of direction. Figure 3 shows two such cases; on 3 May, Figure 3(a), a change of 180 degrees

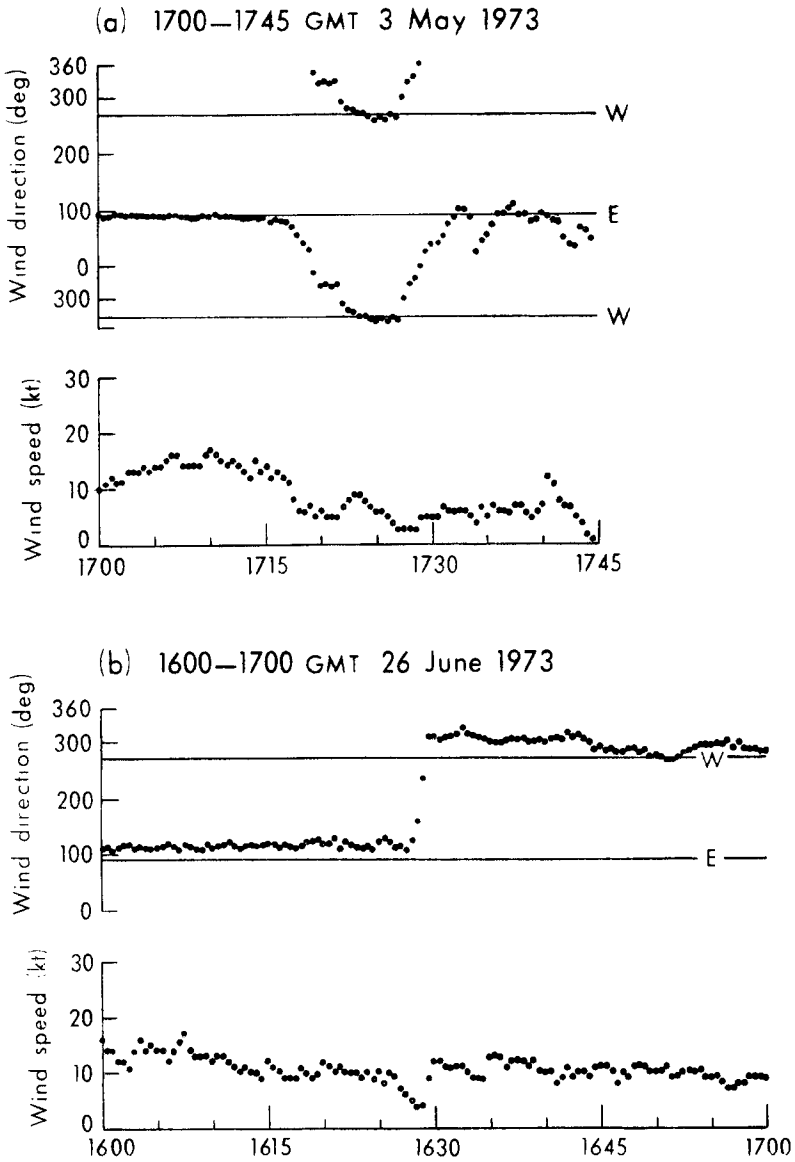


FIGURE 3—EXAMPLES OF SUDDEN LARGE CHANGES IN WIND DIRECTION

over 10 minutes was maintained for only a short period, and on 26 June a 180-degree change took place over 2 minutes and persisted. On both occasions thundery activity was reported in the area and the second undoubtedly marked the passage of an organized frontal system.

TABLE 1(a)—PERCENTAGE FREQUENCIES OF VECTOR DIFFERENCES BETWEEN OBSERVED WINDS, AVERAGED OVER VARIOUS AVERAGING PERIODS, AND ACTUAL 30-SECOND MEAN WINDS, EXCEEDING GIVEN MAGNITUDES, FOR A LAG OF 5 MINUTES

Averaging period <i>min</i>	Magnitude of vector error (knots)				
	2	6	10	14	18
$\frac{1}{2}$	76.9	15.4	2.05	0.52	0.11
2	71.5	11.7	<u>1.68</u>	<u>0.45</u>	0.21
4	69.0	10.5	1.72	0.52	0.23
6	68.8	10.0	1.81	0.63	0.29
8	68.8	<u>9.8</u>	2.03	0.71	0.34
10	<u>68.7</u>	10.0	2.09	0.76	0.39

Minimum values at each threshold are underlined.

TABLE 1(b)—PERCENTAGE FREQUENCIES OF VECTOR DIFFERENCES BETWEEN OBSERVED WINDS, AVERAGED OVER VARIOUS AVERAGING PERIODS, AND ACTUAL 30-SECOND MEAN WINDS, EXCEEDING GIVEN MAGNITUDES, FOR A LAG OF 10 MINUTES

Averaging period <i>min</i>	Magnitude of vector error (knots)				
	2	6	10	14	18
$\frac{1}{2}$	80.3	18.8	3.42	<u>1.10</u>	<u>0.31</u>
2	75.0	15.4	3.05	1.11	0.35
4	72.9	14.0	<u>2.88</u>	1.17	0.44
6	<u>72.3</u>	13.3	3.03	1.23	0.49
8	72.4	13.0	3.09	1.28	0.51
10	73.0	<u>12.8</u>	3.10	1.37	0.50

Minimum values at each threshold are underlined.

Conclusions. Differences between an observed wind and the actual wind encountered some time later can be reduced substantially if the delay is reduced to a minimum. This is more critical than the time over which the observation is averaged. Implicit in this conclusion is the desirability that the anemometer should be near, or slightly upwind of, the touch-down area.

To minimize the r.m.s. error, averaging over 3 minutes or more is best except at very short lags. This reduces the variability of observations in stationary situations at the expense of a slow response to the occasional abrupt change.

Errors in excess of 10 kt can be minimized by using a $1\frac{1}{2}$ -4-minute average except at very short lags when a $1-1\frac{1}{2}$ -minute reading is preferable.

If it is desired to reduce the number of infrequent large errors, greater than about 15 kt, which, on the evidence of this sample, occur on average for about 1 minute in 2000, then a 30-second average is best.

To summarize: a two-minute averaging period appears to be a satisfactory compromise; if it were reduced then the number of large errors, already

very small, would be reduced still further at the expense of many more deviations in the 6–14-kt range; if it were increased, then more encountered winds would be within 2 kt of the observed wind, but there would be more frequent large errors.

It should be noted that the results presented in this paper refer to summer in southern England, and that results for winter may be somewhat different.

Finally, the experiment demonstrated the ease with which remote digital displays of wind speed and direction, averaged as desired, can be obtained from the Mk 5 anemometer system.

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REFERENCES

1. Montreal, International Civil Aviation Organization. Report of the Fifth Air Navigation Conference, Montreal. Doc. 8720, AN-CONF/5, Montreal, 1967.
2. SPARKS, W. K. and KEDDIE, BARBARA; A note on the optimum averaging time of wind information for conventional aircraft landings. *Met Mag, London*, 100, 1971, pp. 129–134.
3. JONES, J. I. P. and PASQUILL, F.; An experimental system for directly recording statistics of the intensity of atmospheric turbulence. *Q J R Met Soc, London*, 85, 1959, pp. 225–236.
4. ACHESON, D. T.; An approximation to arithmetic averaging for meteorological variables. *J Appl Met, Lancaster, Pa*, 7, 1968, pp. 548–553.
5. KAMOMOTO, H.; Determination of time constant of CR circuit used for obtaining mean wind speed. *J Met Res, Tokyo*, 24, 1972, pp. 77–80.
6. PAINTING, D. J.; An analogue direction averaging circuit for the Mark 5 wind system. London, Meteorological Office, 1973. (Unpublished, copy available in the Meteorological Office Library, Bracknell, Berks.)
7. BURNHAM, J.; A note on the turbulence problems associated with take off and landing. *RAF Tech Rep 67240, Farnborough*, 1967.

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NOTE ON ERRORS THAT MAY BE INDUCED BY USING VISIBILITY OBSERVATIONS TAKEN AT GREATER THAN HOURLY INTERVALS

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Summary. Parameters describing the low-visibility regime at John F. Kennedy International Airport, New York, for the period 1959–64 were derived by using observations taken at one-hour intervals. Three-hour-interval observations were simulated using the one-hour observations. Comparison of these data sets indicates that marked errors can be introduced in estimates of frequency of occurrence of very low visibilities and in estimates of consecutive hours of occurrence of low visibilities, by sampling at greater than one-hour intervals.

Introduction. Shellard,¹ in this journal, demonstrated that a 'very satisfactory' estimate of annual fog frequency could be obtained from observations taken at six-hour intervals. Subsequently Kelly² showed that for a specific data set the use of observations taken at three-hour intervals overestimated by only about 4 per cent the total hours of occurrence of fog of 12 hours' duration or more with a visibility of less than 220 yards.

Prior to undertaking an analysis for a study to compare the low-visibility regime at John F. Kennedy International Airport, New York, with that for the adjacent offshore region,³ the effect of the use of three-hour-interval observations as compared with one-hour-interval observations was re-examined.

This examination was necessitated by the initiation of a program at most U.S. Weather Bureau (now National Weather Service) Stations on 1 January 1965 whereby the number of hourly observations punched for recording on magnetic data-processing tape was reduced from 24 to 8 per day. Moreover the offshore station used for the study, Ambrose Light Station, New York, reported visibility only six times per day. This note is presented to demonstrate the substantial errors that can be caused by using visibility observations taken or recorded at three-hour intervals as compared with one-hour intervals.

Data used. The 12-year period 1959-70 was selected for the study, and the data for Kennedy Airport, recorded at one-hour intervals, were therefore available for the 1959-64 segment of the study period. A computer program was written to count the number of consecutive hours, using the one-hour observations, of occurrence of visibilities within selected low-visibility classes. This program was subsequently modified and 'runs' (consecutive hours of occurrence) of low visibilities for sampling at three-hour intervals were generated beginning with the hours 0000 LST (local standard time), followed by 0300 LST, 0600 LST, . . . , 0100 LST followed by 0400 LST, 0700 LST, . . . , and 0200 LST, followed by 0500 LST, 0800 LST, ... For the three-hour sampling the assumption was made that each observation of a visibility represents three hours of occurrence of that visibility, as assumed by Shellard and Kelly. The results are presented in Table I.

Discussion. The purpose of the Kennedy Airport - Ambrose Light Station comparison³ was to examine the characteristics of the offshore low-visibility regime, which could have an important effect upon operations at a proposed offshore 'jetport'. Two areas of deviation in Table I which are the result of three-hour sampling that are significant to these operations are (a) estimates of the frequency of occurrence of very low visibilities, and (b) estimates of consecutive hours of occurrence of low visibilities.

(a) *Estimates of the frequency of occurrence of very low visibilities.* Based on hourly observations, the total occurrence of visibility less than 50 yards is 67 hours (Table I). By comparison, the total hours of occurrence for three-hour-interval sampling are the following (the times in parentheses indicate the first hour of the sampling period, and the percentages indicate the percentage differences from the preceding hourly estimates):

1. 48 hours (0000 LST) -28.4 per cent
2. 75 hours (0100 LST) 11.9 per cent
3. 78 hours (0200 LST) 16.4 per cent.

The data presented by Shellard in his Tables I and II for visibilities less than 44 yards show differences comparable with those above:

Station	Type	One-hour observations	Three-hour observations	Percentage difference
<i>Average number of hours per annum</i>				
Mildenhall	rural	20	14	-30.0
West Raynham	rural	17	13	-23.5
Croydon	urban	21	23	+9.5

Shellard's comment that 'very satisfactory estimates of annual frequency can be obtained using observations made at 0300, 0900, 1500 and 2100 G.M.T.' must be evaluated in the light of what is 'very satisfactory'.

TABLE 1—CONSECUTIVE HOURS OF OCCURRENCE OF SELECTED LOW VISIBILITIES AT NEW YORK/KENNEDY AIRPORT, 1959-64, BASED ON HOURLY AND THREE-HOURLY OBSERVATIONS

		Consecutive hours of occurrence(Y)																																	Total hours Σ/Y	Percentage difference from hourly obs
		Number of occurrences (f)																																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33		
Visibility less than 50 yd																																				
Hourly observations		12	7	5	1	2	0	0	0	0	0	0	1																							
Three-hourly obs																																				
starting at		0000	10	1	1	0	1	0	1	0	0	1	1																							
		0100	19	1	1	0	0	0	0	0	0	1	1																							
		0200	16	1	3	0	0	0	0	0	0	1	1																							
Visibility less than 1/4 n. mile																																				
Hourly observations		115	56	37	19	8	5	8	0	5	2	2	1	0	1	2	0	1	(1)																	
Three-hourly obs																																				
starting at		0000	97	25	46	12	12	12	3	3	3	3	3	3	3	3	3	3	(1)																	
		0100	92	35	11	11	11	11	5	5	5	5	5	5	5	5	5	5	0																	
		0200	102	19	18	18	18	18	2	2	2	2	2	2	2	2	2	2	0																	
Visibility less than 1/2 n. mile																																				
Hourly observations		128	50	46	39	18	14	11	10	4	3	4	0	0	3	2	2	0	0	0	0	0	1	0	0	1										
Three-hourly obs																																				
starting at		0000	130	48	30	17	17	17	8	8	6	6	5	5	7	7	6	1	1	1	1	1	1	1	1											
		0100	122	55	21	21	21	21	5	5	6	6	9	9	9	9	9	2	2	2	2	2	2	2	2											
		0200	121	44	23	23	23	23	9	9	6	6	9	9	6	6	6	2	2	2	2	2	2	2	2											
Visibility less than 1 n. mile																																				
Hourly observations		203	96	67	48	28	31	21	11	9	7	5	4	4	1	6	1	3	1	2	0	0	0	0	0	3	0	0	0	0	0	1				
Three-hourly obs																																				
starting at		0000	185	82	31	31	31	31	16	16	10	10	16	16	10	10	10	7	7	3	3	3	3	3	3	3	0	0	0	0	1					
		0100	177	79	42	42	42	42	12	12	11	11	12	11	11	11	11	7	7	3	3	3	3	3	3	2	1	1	1	1	1					
		0200	181	79	33	33	33	33	18	18	10	10	18	18	10	10	10	10	10	3	3	3	3	3	2	2	1	1	1	1	1					

All times are expressed in Local Standard Time.

The data in the last column of Table I indicate that the percentage of error increases as the visibility class considered decreases. As a measure of deviation (D_t) in per-cent of the three-hour estimates from the related one-hour estimate, let

$$D_t \doteq \text{abs. } D_1 + \text{abs. } D_2 + \text{abs. } D_3,$$

with $D_1 = ((z_1 - X)/X) (100)$; $D_2 = ((z_2 - X)/X) (100)$; $D_3 = ((z_3 - X)/X) (100)$, where z_1, z_2, z_3 are the three-hour estimates of the total hours of occurrence of visibility in a visibility class, and X is the total of hours of occurrence of that visibility based upon one-hour observations. The absolute value (abs.) of the deviations is used because X is the mean of z_1, z_2 , and z_3 and algebraically the sum of the deviations around the mean of a sample is zero.

In order to test the significance of the apparent relationship between D_t and visibility class, additional one-hour-interval and three-hour-interval samples were generated from the data for Kennedy Airport for the two-year period 1959-60 and for the four-year period 1959-62. These data are combined with the data in the last two columns in Table I and are presented as Table II.

TABLE II—VISIBILITY CLASS LIMIT, DEVIATION (D_t) AND TOTAL HOURS OF OCCURRENCE BASED ON ONE-HOUR OBSERVATIONS OF VISIBILITY IN EACH VISIBILITY CLASS (X) FOR THREE-HOUR OBSERVATIONS AT KENNEDY AIRPORT

Visibility class limit yards	1959-64		Sample period 1959-62		1959-60	
	D_t	X	D_t	X	D_t	X
50	56.7	67	56.0	50	114.2	14
506	12.6	700	17.2	464	17.4	218
1012	5.1	1114	8.4	739	4.5	353
2024	3.1	1988	2.2	1323	3.3	658

Plotting deviation (D_t) against visibility class results in an approximately hyperbolic curve. A reciprocal transformation was applied to the values of D_t to obtain a straight-line regression.⁴ The least-squares regression line passing essentially through the origin was computed for the transformed values ($1/D_t$) on visibility class. The resulting regression coefficient was 2.0×10^{-1} . Analysis of variance for the linear regression is presented as Table III.

TABLE III—ANALYSIS OF VARIANCE FOR LINEAR REGRESSION OF THE RECIPROCAL OF DEVIATION ($1/D_t$) ON VISIBILITY CLASS

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-value
Due to regression	1	0.20954	0.04391	96.45518*
Deviation about regression	10	0.02134	0.00046	
Totals	11	0.23088		

* Significant at the 0.1 per cent level.

It is clear from the F -value that an increase in the percentage of error is significantly related to a decrease in the visibility value considered. This is most likely due to the shorter duration of periods of lower visibilities in fog.⁵

(b) *Consecutive hours of occurrence of low visibilities.* Along with the total hours of occurrence of low visibilities, the persistence of low visibility has a marked effect upon airport operations, and thus often has a financial impact upon airport users. 'Bottleneck delays' due to low visibility result in a queueing effect for arriving aircraft. This effect is cumulative with the waiting line, and thus aircraft holding time, reaching its greatest length at the end of the period of curtailed service.⁶ As the length of the waiting period increases, the number of aircraft diversions and cancellations increases.

Table I shows that the longest period of consecutive hours of occurrence of visibility less than $\frac{1}{4}$ nautical mile (n. mile) was 17 hours. By comparison, the samples generated at three-hour intervals suggest occurrences of 18, 21 (2 occurrences), and 24 consecutive hours with visibility less than $\frac{1}{4}$ n. mile. Examination of the left-hand side of Table I reveals that three-hour observations inherently over-estimate the number of three-hour runs for all visibility classes. It is apparent from Table I that marked variation exists between three-hour sampling and hourly sampling as well as among the three-hour-interval samples.

For the Kennedy Airport-Ambrose Light Station study the sample period for the comparison of persistence of low visibilities was shortened from the 1959-70 period to the 1959-64 period for which hourly observations for Kennedy Airport were available. The Ambrose observations had been taken six times per day. Runs at four-hour intervals were therefore generated from the Kennedy Airport observations beginning with the hours 0000 LST, 0100 LST, 0200 LST and 0300 LST. These four samples were compared and the largest number of occurrences for each four-hour interval is reported in Table IV. This technique maximizes the runs of consecutive hours of low visibility at Kennedy Airport and thus results in the most conservative estimate of differences of persistence between Kennedy Airport and Ambrose Light Station. The greater incidence of protracted periods of low visibilities at Ambrose Light Station as compared with Kennedy Airport, shown by the results in Table IV, supports the hypothesis that, in general, sea fogs tend to be prolonged by comparison with land fogs.^{7,8}

TABLE IV—RUNS OF CONSECUTIVE HOURS OF LOW VISIBILITIES, 1959-64, NEW YORK/KENNEDY AIRPORT AND AMBROSE LIGHT STATION, NEW YORK

Visibility	Station	Consecutive hours of occurrence							
		1-4	5-8	9-12	13-16	17-20	21-24	24-30	31-36
		<i>number of runs</i>							
Less than 50 yd	Kennedy	19	2	1					
	Ambrose	24	49	17	4	1			
Less than $\frac{1}{4}$ n. mile	Kennedy	96	22	10	6	1			
	Ambrose	58	91	25	8	4	7	1	3
Less than $\frac{1}{2}$ n. mile	Kennedy	129	53	17	7	2	2		
	Ambrose	72	102	29	10	7	5	1	3

Conclusion. Sampling at greater than hourly intervals can introduce significant errors in estimates of frequency of occurrence of very low visibilities.

When comparing the low-visibility regimes at different stations one should compare statistics derived in like manner from the basic data, even if this involves debasing the statistics from some of the stations where the data are capable of greater resolution.

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REFERENCES

1. SHELLARD, H. C.; The frequency of fog in the London area compared with that in rural areas of East Anglia and south-east England. *Met Mag, London*, **88**, 1959, pp. 321-323.
2. KELLY, T.; A study of persistent and semi-persistent thick and dense fog in the London area during the decade 1947-56. *Met Mag, London*, **92**, 1963, pp. 177-183.
3. HINZ, R. K.; Fog frequency and characteristics at the site of the proposed New York offshore airport as compared with those at J. F. Kennedy International Airport— a preliminary report. New York, American Institute of Aeronautics and Astronautics. First International Conference on Offshore Airport Technology, Vol. I, Presentations at the Conference, New York, 1973, pp. 162-172.
4. SOKAL, R. R. and ROHLF, F. J.; Biometry. San Francisco, W. H. Freeman and Co., 1969.
5. QUINLAN, F. T.; Ceiling-visibility duration estimates and comparisons. Asheville, N. C., U.S. Dept. of Commerce, Environmental Data Service. (Undated, unpublished report, copy available in the Meteorological Office Library, Bracknell, Berks.)
6. HILSENROD, A.; On the economic benefits of fog modification. Washington, D.C., Federal Aviation Administration, Systems Research and Development Service. (Undated draft document, copy available in the Meteorological Office Library, Bracknell, Berks.)
7. BYERS, H. R.; General meteorology. New York, McGraw-Hill, 1959.
8. WILLETT, H. C.; Fog and haze, their causes, distribution and forecasting. *Mon Weath Rev, Washington, D.C.*, **56**, 1928, pp. 435-468.

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MEASUREMENTS OF THE SWING OF A BALLOON PAYLOAD

By J. S. FOOT, E. L. SIMMONS and A. E. WHITTAKER

Summary. An instrument is described for measuring the angular swings of a balloon package. Results are presented from a flight which indicated that the large swings of approximately ± 25 die away rapidly as the rate of ascent is reduced.

Introduction. The measurements were conducted to determine the required angular slew-rates from a balloon-borne sun-seeker, but seem of wider interest because there are a number of experiments in which some knowledge of the angular excursions of a balloon payload are desirable. The apparent solar zenith angle at the package was observed by measuring the output of an upward facing silicon solar cell.

Description of the apparatus. In order to give the solar cell a fairly accurate cosine response and to reduce interference by sky-light, a piece of opal glass and a red glass filter were placed above the cell, while linearity was ensured by using an amplifier which presented a low input impedance. The output of the amplifier was fed into a voltage-controlled oscillator, which modulated a 27.5-MHz transmitter. The cell was mounted at the centre of a 'spider' with arms about 210 mm long suspended by three wires. The cell was levelled by rotating the suspension point with the cell in full sunlight and adjusting until the output was independent of azimuth.

If θ is the mean solar zenith angle and ε the excursion from this, the transmitted frequency is given by

$$f = f_0 + A \cos(\theta + \varepsilon)$$

$$= f_0 + A (\cos \theta + \varepsilon \sin \theta - \frac{1}{2!} \varepsilon^2 \cos \theta + \frac{1}{3!} \varepsilon^3 \sin \theta + \dots).$$

Hence $(f^- - f^+) / (\bar{f} - f_0) \approx 2\varepsilon \tan \theta (1 - \varepsilon^2/6)$, where f^+ and f^- are the frequencies for the angular excursions $\pm \varepsilon$ respectively, $\bar{f}$ is the mean value of the frequency when the excursions are small and f_0 the frequency when the cell is not illuminated. The term in ε^2 can be neglected for values of ε up to 20° so we have

$$\varepsilon = \frac{1}{2} \cot \theta (f^- - f^+) / (\bar{f} - f_0).$$

Solar zenith angles are calculated from the *Nautical Almanac*, so there is no calibration needed except for the levelling referred to above, and a check that a cosine response is obtained and that f_0 remains constant over the expected range of battery voltage and temperature.

Results. The apparatus was flown on 3 occasions of which the last (15 June 1973 at Beaufort Park) is described in detail. On this occasion the balloon ascent was controlled by a baroswitch-actuated valve and a controlled leak. Figure 1 shows the balloon height measured by radar plotted against time. The baroswitch was set to actuate at about 15 km. With the leak provided, 0.3 m of 32-mm-diameter pipe, it took approximately 20 minutes to lose free lift and start descending. Figure 2(a) is representative of the first 30 minutes of the flight. The amplitude of swing thereafter increased until minute 56, by which time the swing had become quasi-periodic with large and variable amplitude, as shown in Figure 2(b). As the rate of ascent began to decrease the amplitude decreased until minute 71, when the ascent rate was less than 1 m/s and the swing was less than $\pm \frac{1}{2}^\circ$. Figure 2(c) shows that from minute 71 to 74 the swing remained at this low level, but built up after this time when the balloon was descending at a speed greater than 2 m/s. The three supporting wires interrupted the sunlight as the sonde rotated and gave rise to a fine structure on the trace which is not shown in the Figure. The speed of rotation during the period from minute 71 to minute 74 was 16 rev/min. As the rate of descent increased the oscillation built up rapidly, but then decreased towards minute 92 (Figures 2(d) and

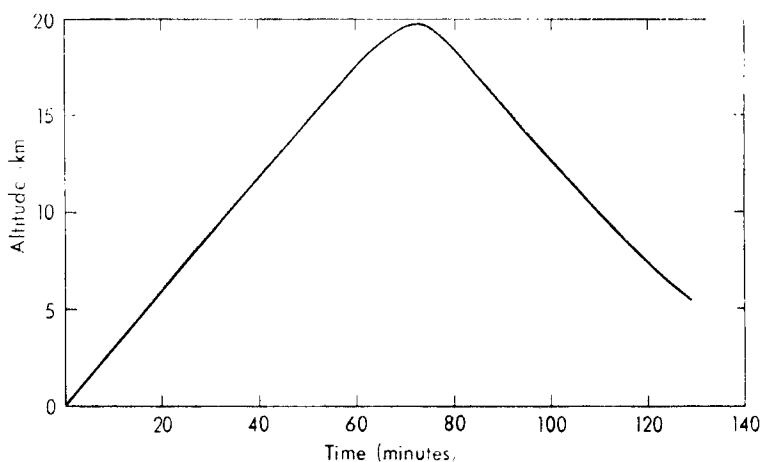


FIGURE 1—ALTITUDE OF THE BALLOON MEASURED BY RADAR VERSUS TIME

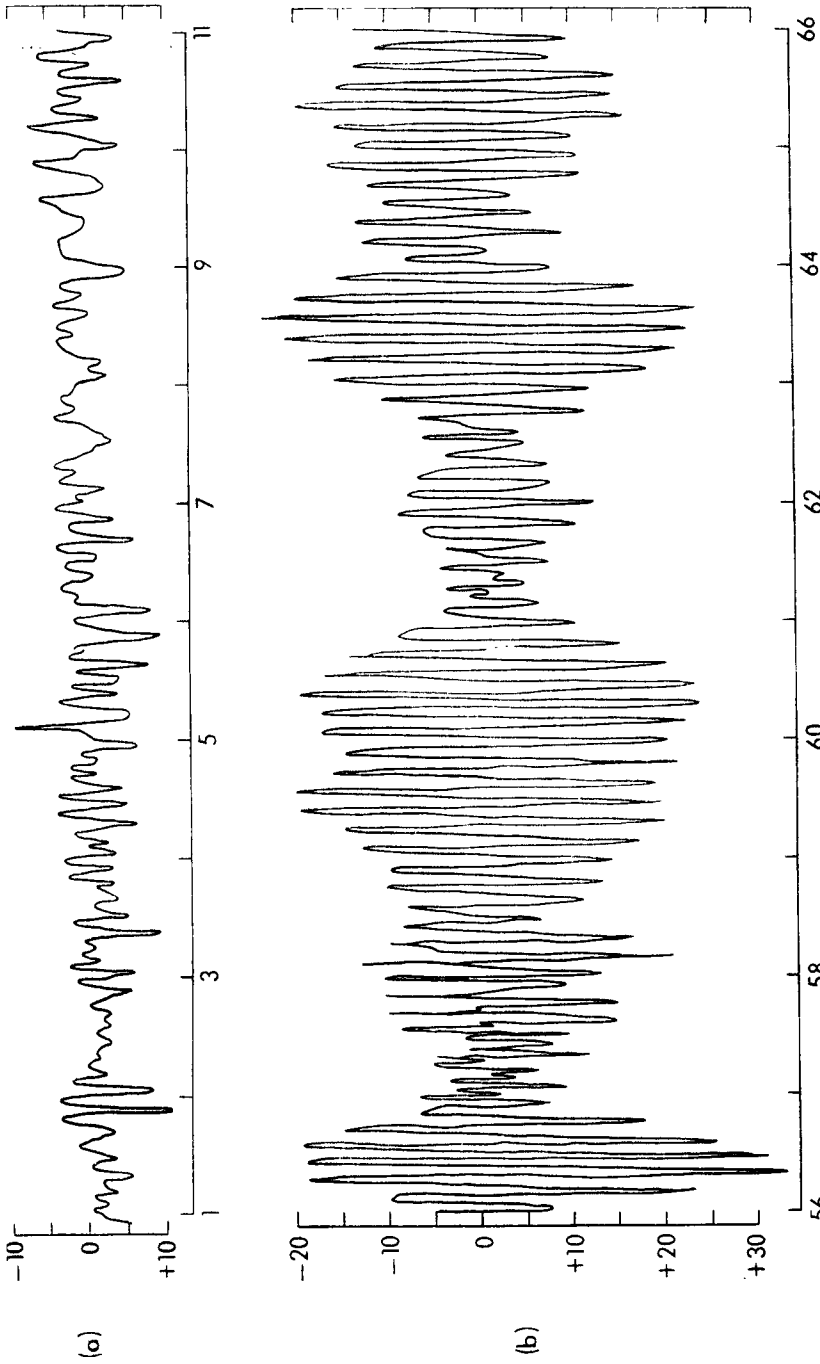


FIGURE 2 — TRACINGS OF SELECTED PORTIONS OF THE RECORDED OUTPUT OF THE TELEMETRY FREQUENCY METER
The vertical scale gives the angular excursion in degrees and the horizontal scale the time in minutes.

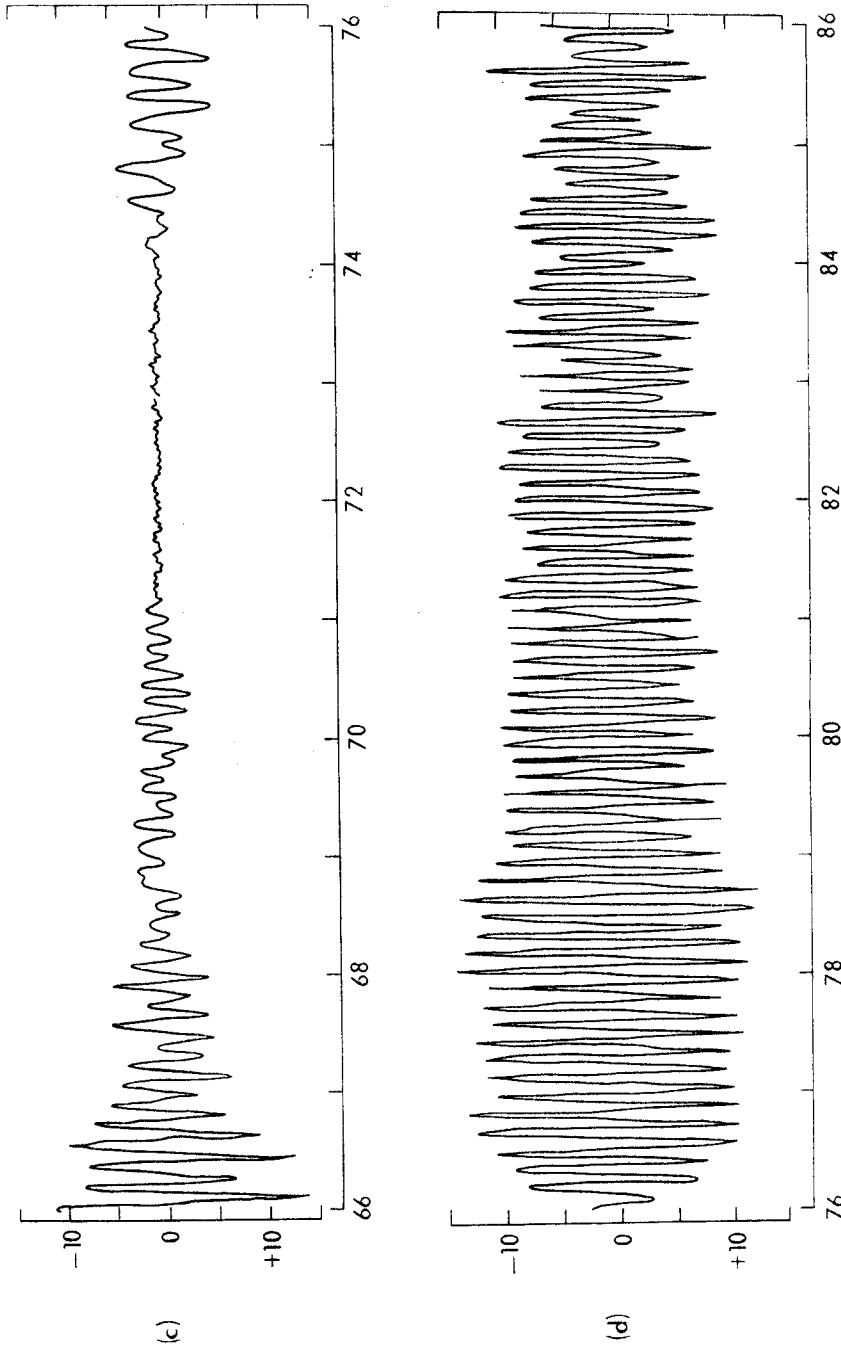


FIGURE 2 —continued

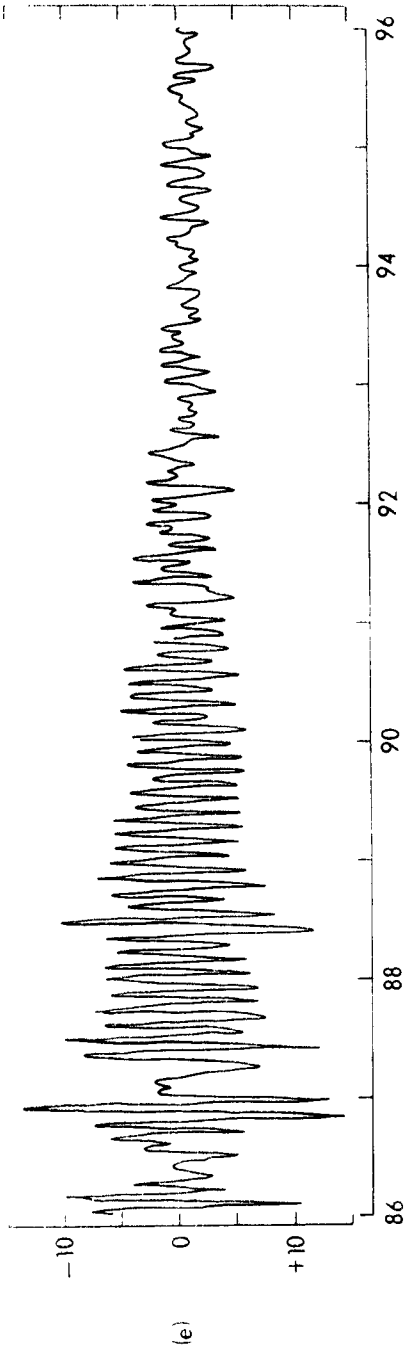


FIGURE 2 *continued*

2(c)) and remained similar until loss of contact at minute 129. On the descent the aerodynamic properties were different from those on the ascent, since the sonde was supported by the partially deflated balloon assisted by a paper parachute attached to the radar target in the conventional manner.

Discussion. The flight achieved its purpose in demonstrating the small amplitude of swing encountered under the conditions under which the sun-seeker will be used, when the descent rate is less than 2 m/s. The swinging at higher speeds represents a number of features which are only partially understood. They are apparently fairly typical because similar results were obtained on other flights.

The period, calculated from those regions where the swinging appeared roughly sinusoidal, was 9.8 s on the ascent, decreasing progressively during the descent to 7.1 s. The length of the train, excluding the balloon, was 27 m, and the period on the ascent is that for a simple pendulum of length 24 m, so one may picture the whole system pivoting about a point near the balloon. On the descent the equivalent simple-pendulum length decreased to 12.5 m. It is difficult to account for this short period except in terms of strong forcing.

The maximum amplitude of swing was $\pm 25^\circ$, which corresponds approximately to a periodic horizontal velocity of the package relative to the balloon of magnitude 7 m/s.

There does not appear to be any correlation between the swinging of the balloon and the wind shear calculated from the radar data. In particular the regions of shear traversed on ascent and descent must have been similar, but the pattern of swinging is noticeably different. We conclude that the swinging is mainly controlled by the aerodynamics of the balloon itself so that the results obtained are not peculiar to one day and a particular relation between the direction of the sun and the wind-shear vector.

Acknowledgements. Thanks are due to Messrs E. W. C. Harris and J. Fitzsimons for help with the launching of the balloons.

551.553.11

A SHORT NOTE ON A SEA-BREEZE CROSSING EAST ANGLIA

By M. F. SMITH

(Meteorological Office, Honington)

Summary. A remarkable sea-breeze front with considerable radar echoes but no significant cloud or weather was tracked 85 nautical miles inland from the coast of East Anglia.

Introduction. This note describes the passage of a sea-breeze front across East Anglia on 14 June 1973.

Synoptic situation. At 15 GMT an anticyclone was centred over the southern North Sea and Low Countries with a south-westerly gradient wind of 15 kt* over southern England.

* Distances, heights and speeds are given in traditional British units. Conversion factors to metric units are: 1 knot $\approx$ 0.5 m/s; 1 mile $\approx$ 1.6 km; 1 foot = 0.3048 m; 1 nautical mile $\approx$ 1.86 km.

Radar echo. Honington Air Traffic Control radar reported at 18 GMT a line of echoes following the shape of the coastline and about 5 miles wide from the north Norfolk coast, over Honington, to Essex. This anomalous propagation slowly dissipated after 19 GMT.

Temperature gradient (Figure 1). The sea surface temperatures were generally 12°C and maximum coastal temperatures were in the range 14–18°C while temperatures inland reached 20°C.

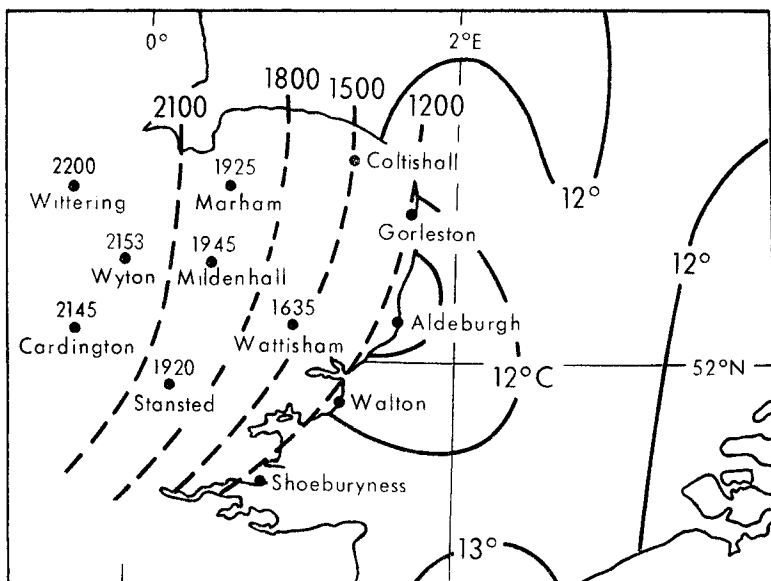


FIGURE 1 —MEAN SEA SURFACE TEMPERATURE ISOTHERMS 11–15 JUNE 1973 AND POSITIONS AND TIMES OF SEA-BREEZE REPORTS

Times are in GMT.

The sea-breeze front. A glider pilot from Tibbenham airfield (about 15 miles south-south-west of Norwich) reported that the front extended to 4000 ft when it passed over Tibbenham at 15 GMT. This height is supported by the 12 GMT Hemsby ascent (Figure 2). The Cardington BALTHUM ascent at 2241 GMT showed cooling to about 2100 ft (Figure 3). Backing winds on the 12 GMT Hemsby ascent and on a PILOT ascent from Shoeburyness at 1035 GMT suggested cold advection (see Table I).

Progression of the sea-breeze front (Figure 1). South-easterly winds occurred on the East Coast by about 12 GMT. The front progressed at approximately 5 kt and passed through Honington at 1810 GMT with a maximum gust of 20 kt, a temperature fall of 4 degC and a rise in relative humidity of 20 per cent. After 18 GMT the front accelerated and reached Cardington at 2145 GMT and Wittering at 22 GMT. It was not possible to follow the penetration any further as winds were light and radiation was taking place.

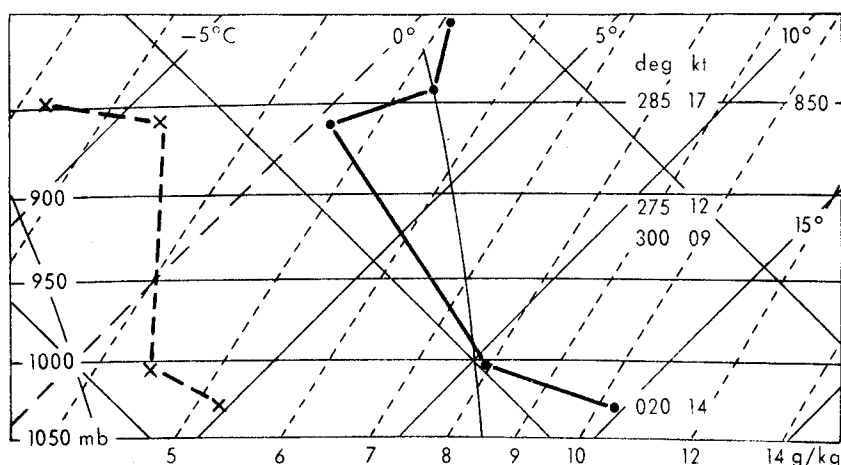


FIGURE 2—HEMSBY RADIOSONDE ASCENT FOR 12 GMT, 14 JUNE 1973

—•— Dry-bulb temperature x --- x Dew-point temperature

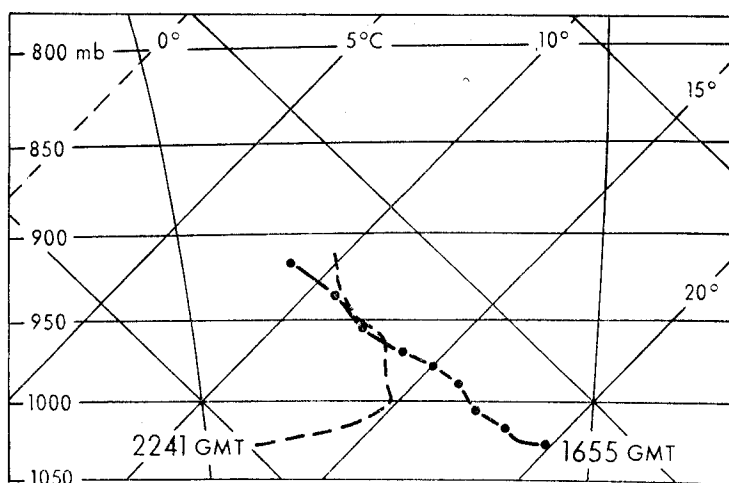


FIGURE 3—CARDINGTON BALTHUM DRY-BULB CURVES FOR 14 JUNE 1973

TABLE 1—SHOEBURYNNESS PILOT ASCENT AT 1035 GMT, 14 JUNE 1973

Height metres	Wind direction degrees from north	Wind speed knots
10	115	08
150	120	12
300	110	08
450	075	03
600	030	07
750	340	10
1000	330	11

Discussion. The progress of this sea-breeze front was remarkable as it penetrated 85 nautical miles inland against a 10-kt westerly component to a height of 5000 ft and the initial temperature differential was only 8 or 9 degC. There was no low cloud when the front passed Honington and only small amounts had been reported over East Anglia throughout the afternoon. Some patches of altocumulus and cirrus were reported. The assumption was made that the anomalous propagation (anaprop) was attributable either to the inversion at about 4000 ft or to the inversion created near the surface by the sea-breeze.

REVIEWS

Advances in satellite meteorology, edited by A. I. Burtsev, P. N. Belov and Sh. A. Musaelyan. 240 mm × 165 mm, pp. vi + 305, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem and London), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex. 1973. Price: £7.50.

This is the first volume of a collection of papers dealing with varied aspects of satellite meteorology. Thirty papers and their bibliographies demonstrate the intense interest and activity in satellite research in the U.S.S.R. The satellite is evidently seen as providing the answer to many of our present meteorological problems!

As might be expected at the present stage of progress, only a modest number of papers deal with the elementary subjective aspects of photographic interpretation of visual pictures. Of interest to users of automatic picture transmission (APT) photographs will be the papers 'Utilization of satellite information in synoptic practice' by E. P. Dombkovskaya and V. F. Chernova, 'Some parameters of cyclonic vortices' by T. P. Popova, and 'The cloud field and cyclogenesis' by T. P. Popova and T. A. Irisova. Mesoscale features are investigated in 'Cellular convection in a vorticity field' by N. F. Vel'tishchev and A. A. Zhelnin, and 'Cloud eddies in wakes of islands' by T. Kh. Geokhlanyan.

Other papers in the same tradition but with a geographical emphasis are concerned with the more usual aspects of synoptic processes, e.g. 'Depressions and cloud systems over the Pacific Ocean' by Yu. V. Kurilova and I. R. Egorova. From this, the following extracts which agree with our own experience are worth quoting: 'The occlusion process in fast-moving depressions over the ocean occurs in a shorter period than that displayed on synoptic maps by frontal analysis', 'according to the cloudiness, occluded fronts occur in the form of strongly-bent spirals. Thus, satellite information leads to the conclusion that Bergeron's ideas about backbent occlusions are near the truth' and 'according to satellite data, the cloud system of an occlusion is maintained longer than the occluded front itself on synoptic maps'.

In many meteorological services, subjective interpretation of APT photographs is used as a basis for the laborious preparation of nephanalyses. Here is an obvious need for automatic picture processing by computer. Aspects of this problem are tackled in 'Computer processing and analysis of TV cloud

photographs' by I. S. Solov'eva, D. M. Sonechkin and V. F. Kharitonov; the corresponding problem of infra-red interpretation is dealt with in 'Automatic analysis of cloud cover by infra-red photography of the earth from Meteor satellites' by D. M. Sonechkin and L. M. Soskin. Many other papers deal with infra-red measurements and include problems of determining cloud tops, of vertical temperature profiles and of radiation flux. Also included is the computation of heat flux for use in numerical weather forecasting.

Objective analysis is an obvious field for the application of satellite data and the problem of using Satellite Infra-Red Spectrometer (SIRS) data must be well known to most forecasters. One paper deals with the effectiveness of utilizing cloudiness data obtained from satellites in objective analysis of the wind field, and another paper with the calculation of geopotential fields at various atmospheric levels from data on the overall cloudiness and temperature. With primitive-equation models, the moisture field is of great importance and this is reflected in the fact that five papers are devoted to the analysis of atmospheric moisture.

Apart from one or two instances where interest is mainly theoretical, the papers are characterized by a refreshing directness of approach, a somewhat naïve appeal to statistical method and a concern for the practical need. They will be a source of interest and knowledge to practising forecasters and others concerned with the application of satellite techniques to current problems. The translation is adequate and very few errors were noted.

T. H. KIRK

Modifying the weather by W. R. D. Sewell *et alii*. 225 mm × 150 mm, pp. xvi + 349, *illus.*, Department of Geography, University of Victoria, Victoria, British Columbia, Canada. 1973. Price: \$4 (paperback).

Despite its title this volume has little to tell about the techniques of weather modification or the science of atmospheric physics upon which it must be based. The authors are concerned almost entirely with the impact of weather modification upon individuals and on society, if and when any substantial changes in weather can be achieved by artificial means. They consider how the community should decide whether the benefits of weather modifications for some activities outweigh its less welcome effects on others, also what organizations are needed to control and manage weather modification and what its potential effects may be.

The book is made up of the background papers presented at a 'Symposium on Human Interactions with the Atmosphere' held at Boulder, Colorado in October 1972. Some 50 people attended and a synthesis of the discussion is incorporated in the papers as published. There are nine authors, each having written one chapter except for one with joint authorship. Some overlap is inevitable, but the topics covered are broadly: social research on the impact of weather modification, public concern on the scientific response to it, ecological effects, urban and agricultural effects on climate, assessment of benefits and political aspects. Dr W. R. D. Sewell contributes an introductory survey and final summary.

The reader will probably ask himself whether it is a good thing that this book has been published, or indeed whether it was appropriate to hold a

symposium on human interactions with the atmosphere. Although there are some local weather changes which can be caused by man's activity, deliberate or accidental, it is not the local clearance of cold fog or the urban heat island on a winter night which are the concern of the authors. Their main discussions centre around rainfall augmentation, hail suppression, hurricane modification and other activities with a potentially wide impact. By presenting them as public issues of importance, the book necessarily creates the impression that a major control over the weather will soon be achieved. This is not so, and if rainfall augmentation amounts at most to 10 or 15 per cent, regarded by many responsible scientists as optimistic even in favourable locations, it is doubtful if the public would be aware of any change in the weather regime unless told by the meteorologist. Is it then wise to initiate a public debate among non-scientists on the social implications of weather modification when the scientific justification for expecting any significant impact is so slight, and the scientist can give no valid advice on what artificial weather changes are possible?

In a number of places the book criticizes the scientists who advise that funds to develop weather modification should be channelled primarily into meteorological research and thus be used to develop further the activities from which scientists personally benefit. However, this is, surely, better justified than devoting substantial funds to social surveys and development of a management structure for projects which as yet have no adequate technical basis.

The scientific reader of this volume will, however, be given a useful reminder of the social and political background within which the applications of science must be developed. Only in rather restricted fundamental fields can scientific research be regarded as an end in itself. The meteorologist cannot ignore the applications of his studies, although he may well question whether there is a need for the elaborate studies of their implications which are advocated by the authors. The normal machinery of government has handled issues of far greater importance in the past without social surveys and cost-benefit analysis, etc. If issues of peace and war, public health, finance, etc. can be handled by parliamentary debate and the machinery of democracy, why does weather modification need special treatment?

On the more technical level the scientific reader will find interest in Dr Chagnon's bibliography of urban and agricultural effects on climate although his review of it may be regarded as somewhat uncritical. Dr Sewell's opening review of the history of weather modification in the U.S.A. and Dr Holden's account of some of the politics behind it will also interest the professional reader.

J. S. SAWYER

OBITUARY

It is with regret that we record the death on 6 January 1974 of Mr A. R. Belton, Higher Scientific Officer, Met. O. 12.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked "for Meteorological Magazine."

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AN INDEX OF PACK-ICE SEVERITY OFF NEWFOUNDLAND AND ITS SECULAR VARIATION

By M. K. MILES

Summary. From the available observations of the edge of pack ice off Newfoundland an index has been formed for each year since 1920. This index is an attempt to represent the area of maximum extent, usually reached in April. The decadal means of this index show a slow decrease in the frequency of severe occurrences up to 1950 with a rapid fall to zero in the decade 1961–70.

There is a clear connection between the decadal means and the strength of north-westerly flow off the coast of Labrador. The greatly reduced amount of pack ice in the last two decades can in part be attributed to the reduction in the vigour of the North Atlantic winter circulation, but there is an indication of a lag of some 20 years which may indicate that the strength and temperature of the Labrador current is an important controlling factor.

Introduction. April is the month in which pack ice usually reaches its greatest eastward and southward extent near and over the Grand Banks off Newfoundland. The additional sea area covered with ice in a severe season compared with a light season is comparable to that of the United Kingdom, and represents a volume of ice at least 10 times as great as that carried into the Atlantic as icebergs in a heavy year. It therefore seems worth while to have an index related to this area for as many years as possible. The following data sources were used in forming an index:

- (a) Maps of the edge of the 'field ice' for 1920–39 held in the Meteorological Office.
- (b) Profiles of the edge of the 'field ice' for 1946–55 given by Tunnell.¹
- (c) United States Coast Guard bulletins and ice maps prepared by the Meteorological Office.

Formation of index. The relation of the maximum eastward and southward extent of the ice in April with an index of icebergs off Newfoundland as given by Groissmayer² and Corkum³ was examined separately, and it was concluded that an index formed by adding the longitude and latitude of these would be a reasonable indicator of the ice situation. The greatest eastward extent was to 45°W in 1921 and the least was to 53°W in 1970. The greatest southward extent was to 42½°N in 1921 and the least to 51°N in 1971. Thus the index for 1921 comes to 87½ and indicates the most severe occurrence in the period while the index of 102½ for 1971 represents the lightest occurrence.

The annual indexes for the period 1920-73 are given in Table I. There is not enough information to form an index for the years 1940-42 (inclusive) but they are described in the United States Coast Guard bulletins as being all three very light ice years.

TABLE I — INDEXES OF PACK ICE OFF NEWFOUNDLAND IN APRIL

	0	1	2	3	4	5	6	7	8	9
192—	91	87½	91	90	99	97	90	91½	96	89½
193—	96	100	91½	93	91½	89½	95	96½	92½	90
194—	—	—	—	95	92	92	91	95½	94	97½
195—	90½	98	98	94½	93	93	95½	91	100	95½
196—	96½	97	98	98	99	99½	102	98	102	102
197—	102	102½	98	92½						

Low values indicate severe ice, high values light ice.

The absolute values of such an index cannot be a completely accurate measure of the extent of the pack ice in any one season for several reasons:

- (a) Errors in determining the edge of open pack ice (about five-tenths cover).
- (b) Differing shapes of the ice edge.
- (c) Extremes sometimes occurring in late March and even in May.

However, they should give a fairly reliable indication of whether the pack ice was heavy, moderate or light in individual years, and the decadal means should reveal any strong secular trend that there may be.

The 51 values have been divided into three nearly equal groups with the following tercile boundaries:

- Tercile 1 (light ice) ≥ 98 ;
- Tercile 2 (moderate ice) < 98 and ≥ 93 ;
- Tercile 3 (heavy ice) < 93 .

Secular variation of the index. The distribution of light, moderate and heavy years in the successive decades together with decadal means of the index are given in Table II. From the average values of the index, and from the frequency of severe occurrences, it is clear there has been a reduction in the amount of pack ice over the Grand Banks during the period. The reduction was quite slow until the late 1940s, and was very marked from the late 1950s.

TABLE II — DECADAL MEANS OF PACK-ICE INDEX OFF NEWFOUNDLAND AND NUMBERS OF HEAVY, MODERATE AND LIGHT YEARS

Decade	Mean index	Number of years		
		Heavy	Moderate	Light
1921-30	92.7	7	2	1
1931-40	93.3 (9 years only)	5	3	1 (or 2 if 1940 taken as light)
1941-50	93.4 (8 years only)	4	4	0 (or 2 if 1941 and '42 taken as light)
1951-60	95.5	2	5	3
1961-70	99.7	0	2	8

It is interesting to compare this change with other known climatic trends during this period. Schell⁴ has shown that the number of icebergs counted each year south of 48°N off Newfoundland is related to the strength of the north-westerly winds off Labrador during December to March, so it is reasonable to think that the latter may also be related to the amount of pack ice. The index used here for the strength of the north-westerlies is the average

pressure difference between $50^{\circ}\text{N } 60^{\circ}\text{W}$ and $60^{\circ}\text{N } 50^{\circ}\text{W}$ for the months December, January and February. The decadal averages of this pressure difference are shown in Figure 1 which also contains the decadal means of the pack-ice indexes.

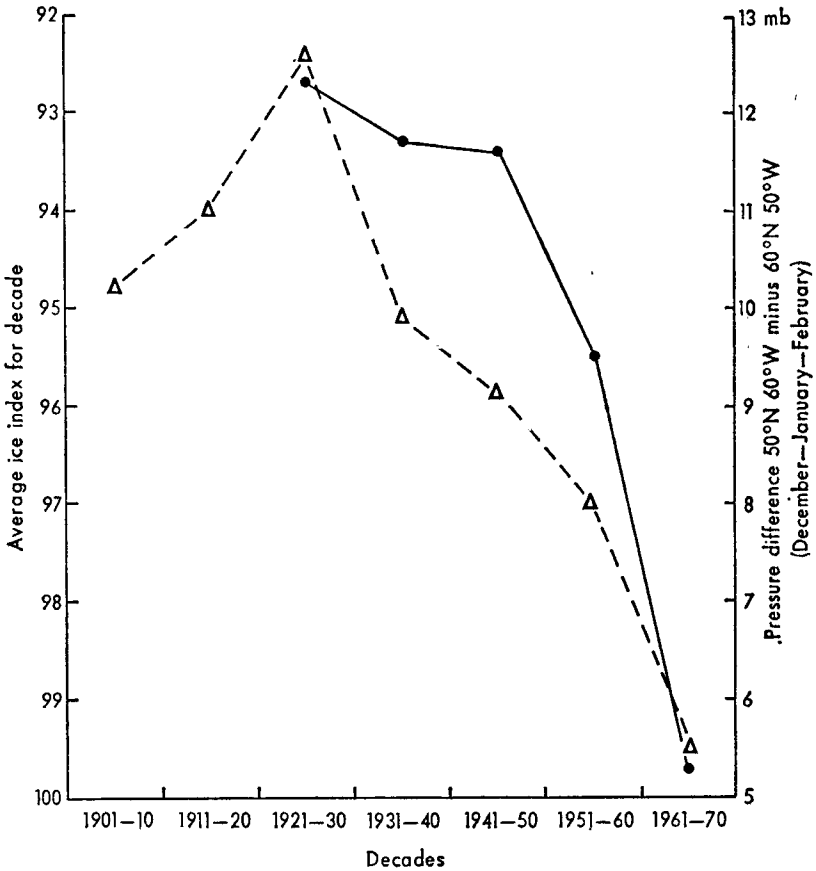


FIGURE 1 — DECADAL MEANS OF ICE INDEX OFF NEWFOUNDLAND AND OF INDEX OF NORTH-WESTERLY WINDS FOR THE COAST OF LABRADOR

● — ● Ice index off Newfoundland.
△ — — — △ Index of north-westerly winds for coast of Labrador.

The reduction in the amount of pack ice is clearly related to the reduction in the strength of the north-westerly winds, which is a reflection of the well-known decrease in the average intensity of the Iceland low during the months of December, January and February over the period 1930-70. There is, however, a distinct hint of a lag in the reduction of ice behind the decline in the north-westerly flow. This hint is confirmed when note is taken of the secular change of air temperatures at stations on the west coast of Greenland. The decadal means of the average winter temperature for Jakobshavn ($69^{\circ}\text{N } 51^{\circ}\text{W}$) and Godthaab ($64^{\circ}\text{N } 52^{\circ}\text{W}$) are given in Figure 2 together with the ice indexes, and show a steep rise in the 1920s with maintained higher values in the decades

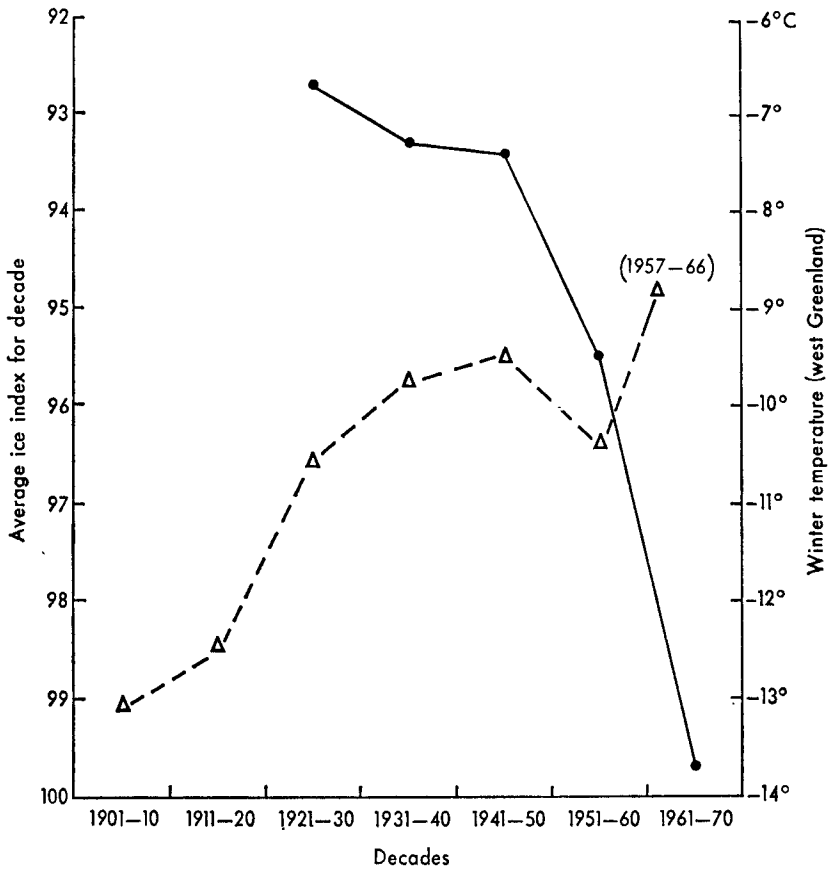


FIGURE 2 — DECADAL MEANS OF ICE INDEX OFF NEWFOUNDLAND AND OF WINTER TEMPERATURE FOR WEST GREENLAND

● — Ice index as in Figure 1.
 Δ — — — Δ Decadal mean winter (December–January–February) temperature for west Greenland ((Jakobshavn + Godthaab)/2).

1931–40 and 1941–50, i.e. for nearly two decades before the substantial reduction in the ice indexes. Among factors likely to be responsible for this lag are:

- a lag in the warming of the source regions of air brought down the Labrador coast in winter compared with the warming in east Greenland,
- a secular change in the strength and/or temperature of the Labrador current, and
- a secular change in the average northern limit of the Gulf Stream south of Newfoundland in the late winter and early spring.

The examination of these factors, should the available data be adequate, may provide some insight into the time scale of interrelated processes bound up with the North Atlantic winter circulation.

Finally, it is worth noting that the increased amounts of ice reported in this

area in the springs of 1972 and 1973 (in 1972 mainly off Labrador, hence the not very high value of the index) were accompanied by values of the north-westerly index typical of the 1920s and 1930s.

REFERENCES

1. TUNNELL, G. A.; Incidence of ice in the approaches to North America during the decade 1946-1955. *Mar Obsr, London*, **31**, 1961, pp. 78-85.
2. GROISSMAYER, F. B.; Schwere und leichte Eisjahre bei Neufundland und das Vorwetter. *Ann Hydrogr, Berlin*, **67**, 1939, pp. 26-30.
3. CORKUM, D. A.; Performance of formula for predicting the iceberg count off Newfoundland. *J Appl Met, Lancaster, Pa*, **10**, 1971, pp. 605-607.
4. SCHELL, I. I.; On the iceberg severity off Newfoundland and its prediction. *J Glaciol, Cambridge*, **4**, 1962, pp. 161-172.

551.501.8: 621.396

THE USE OF WEATHER-RADAR DATA IN COMMUNICATION ENGINEERING*

By T. W. HARROLD

Summary. Precipitation particles attenuate radio signals above a frequency of about 10 GHz. In planning communication links statistical information concerning the attenuation is required. In this review current methods of obtaining this information, including the use of weather radar, are summarized.

Communication problems caused by precipitation. The use of microwave frequency bands for communication links is such that the communication engineer is compelled to use increasingly high frequencies in order to find an available band. The reliability of links above about 10 GHz (3-cm wavelength) is significantly influenced by attenuation (fading) due to precipitation particles. The attenuation per unit distance at a given rate of rainfall increases with frequency, so the importance of attenuation will increase as the higher frequencies are exploited. A further problem is that the scattering (as opposed to attenuation) of radio energy by precipitation at frequencies shared by terrestrial and satellite communication systems is a significant source of potential mutual interference in these systems. The problems are such that the occurrence of precipitation will be a decisive factor in the design and operation of future communication links.

Methods of solution. One method of improving the reliability of a high-frequency communication system is to design the system with the distance between repeater stations sufficiently small that the probability of significant attenuation is reduced to an acceptable level, say a few seconds per year. This entails knowing the probability of attenuation along the path. Another means of improving the reliability is to use the concept of space (path) diversity. For terrestrial links this entails having two or more paths between terminals, positioned so that the probability of both paths being affected by significant attenuation at the same time is at an acceptable value. For earth-space links more than one receiving station has to be employed. The planning of a diversity system thus requires statistics of the mesoscale distribution of precipitation.

*A review based on relevant discussions at the Inter-Union Commission for Radio Meteorology Colloquium on the Fine Scale Structure of Precipitation and Electromagnetic Propagation which was held at Nice, France, on 23-31 October 1973.

It is also possible that the operation of a communication link would be improved if warning of an 'outage' arising from heavy precipitation could be given.

Techniques for obtaining attenuation data

(a) *Direct measurements.* The most direct, but not necessarily the most satisfactory, approach is to measure the attenuation. Existing methods of obtaining data relevant to the planning of earth-space links are:

- (i) Use of transmissions from satellites. A signal dynamic range of about 40 dB and a moderate amount of data can be obtained but a major disadvantage is cost; costs are less for smaller dynamic ranges.
- (ii) Use of the sun as a microwave source. The usable signal dynamic range is 25–30 dB but only a small amount of data can be obtained. The cost of the receiving equipment is about £25 000.
- (iii) Use of sky emission radiation. A larger amount of data can be obtained and the equipment cost is smaller, about £17 000, but the usable dynamic range is only about 10 dB.

These methods do not provide any information concerning suitable locations of the paths in a diversity system unless more than one receiving station is used.

For terrestrial links the only method of obtaining attenuation measurements directly is to use an existing link or establish a new one. In order to study a diversity system several links are required.

Only a limited amount of data can be gathered by these methods and careful interpretation is required if conclusions from these data are applied to other localities or in planning future systems.

(b) *Use of rain-gauge data.* The most practical, inexpensive and widely used method of obtaining attenuation statistics is by the indirect means of using existing surface rain-gauge data. Rate of rainfall (R) is related to the attenuation (A) by an empirical expression of the form $A = CR^d$, where the constants C, d depend on the drop-size distribution of the rain. The advantage of the method is that rainfall data are available from many parts of the world and for sufficiently long periods of time. (In planning a link, which has a lifetime typically of 20 years, it has been found that statistics derived over the previous 15 years are more representative of the period than longer-term statistics.) Difficulties in deriving attenuation statistics from rain-gauge data are that:

- (i) The statistics are required over periods of a minute or less; they generally have to be derived from rainfall records with a coarser time resolution so that errors are introduced, particularly for high rates of rainfall.
- (ii) Statistics along a line are required, so some spatial model of the precipitation has to be applied to the point data from the rain-gauges and this introduces further errors.
- (iii) The attenuation along a line above the surface of the earth is derived from a relationship between rate of rainfall and attenuation. There is a theoretical basis for this relationship in the absence of vertical air motion, but this condition is unlikely to be met in many of the short-period heavier rates of rainfall of interest to the communication engineer so additional errors in the predicted attenuation will be introduced.

A development of the use of rain-gauge data has been the establishment of lines of short time resolution rate-of-rainfall recorders to measure line rainfall directly. This minimizes errors (i) and (ii) above and also permits an improved model relating point to line rainfall to be developed which can be applied to other point-rainfall data in the same locality. However, error (iii) is still present. A further disadvantage is that the setting up and particularly the running of a number of rainfall recorders is costly. For example, the running of and processing of data from a network of 60 magnetic-tape rain-gauges in North Wales costs over £30 000 per annum.

(c) *Use of disdrometer data.* A disdrometer measures the drop sizes of the rainfall. With this knowledge the attenuation can be computed directly, rather than by using an empirical relationship as in (b). This is therefore a more accurate means of estimating attenuation but has the disadvantage that the data required are only available for short periods and from a few locations.

(d) *Use of weather-radar data.* An alternative to either direct measurement or indirect estimates from rain-gauge data which is being used increasingly in deriving attenuation statistics is the use of quantitative data from a weather radar. The attenuation (A) is estimated from measurements of the radar reflectivity factor (Z) by using an empirical relationship of the form $A = E.Z^f$, where E and f are constants related to the raindrop size distribution. By comparing attenuations estimated in this manner with simultaneous direct measurements using a satellite, Strickland¹ showed that the standard error in the radar-derived estimates was less than 0.3 dB for 1 dB of attenuation, increasing to about 0.75 dB (≈ 18 per cent) at 8 dB of attenuation. Advantages of this method over the use of rain-gauges are:

- (i) A large area (about 10^4 km^2) is observed from a single installation. Many links can be simulated within this area so that a large data sample can be obtained in a short period.* The extensive coverage is also an advantage when planning a diversity system because the mesoscale distribution of attenuation as well as line statistics are then required. These can be derived from networks of rate-of-rainfall recorders, but such networks are expensive to establish and maintain and the uncertainties in estimating attenuation from rainfall data remain. It is simpler to use weather-radar data in deriving the mesoscale information. For example, it is now well known from such data that precipitation on the mesoscale is often banded; any preferred orientation or locality of these bands in a particular region would be very significant factors in the siting of communication links.
- (ii) Attenuation and radar reflectivity both depend on the volume concentration of drops, whereas rate of rainfall is a flux which depends also on the vertical air motion. Attenuation calculated from a surface rate of rainfall will not be the same as that aloft if there is vertical air motion. As a simple illustration, consider a volume concentration of N drops/cm³

* Note. The simulation of a number of links is not necessarily equivalent to obtaining a number of years' data over one link because meteorological conditions during the limited time sample may not be representative of the longer period. An example of this is provided by the summer of 1973 in England. Weather-radar data would have permitted statistics of attenuation in an extreme weather type—heavy thunderstorms—to be obtained which might have taken centuries to obtain by using one experimental link and as such might have been valuable; however, the data sample would not have been representative of more typical seasons.

all of the same size and with a still-air fall velocity of 5 m/s falling into a rain-gauge. If at a higher level the drops were within a downdraught of 2 m/s, the volume concentration would be $5 N/7$ drops/cm³ (excluding a small effect due to the horizontal divergence of the flow) and the attenuation would be only 71 per cent of that estimated from the surface data. The magnitude of the error arising from using surface rain-gauge data can therefore exceed that in the radar method.¹

Disadvantages of using weather radar to obtain the required data are:

- (i) The cost of a suitable weather-radar station, which is between £50 000 and £100 000. This is prohibitive compared with the costs of using existing rain-gauge data or a direct measurement system, but it may be comparable to the cost of a rain-gauge network developed for the specific purpose of measuring attenuation.
- (ii) The radar beam, which is usually between 0.5° and 2° wide, is an order of magnitude larger than the beam along a communication path, so that the rainfalls may not be the same. This restricts the value of the radar data in estimating path attenuation, especially beyond a range of about 50 km. Further, at times the radar beam may extend in height to the melting layer, in which case the echo intensity cannot be related to attenuation as accurately as when the beam is entirely within rain. This is also the case when hail is present within the beam. (In this circumstance a rain-gauge may also provide an erroneous measurement.)

In those parts of the world where radar data do not exist, planning must at this stage be based largely on interpretation of rainfall records. However, quantitative weather-radar data are becoming increasingly available in various parts of the world for meteorological and hydrological applications. Where such data do exist it seems preferable to use them to derive attenuation statistics along a line rather than rain-gauges, which provide a less accurate estimate, or direct measurements, the equipment for which is less readily available. In regions where additional information is required radar may well be the most effective means of obtaining it.

The present and possible future situation in the United Kingdom.

Attenuation statistics in the United Kingdom are derived from routinely available rate of rainfall records in the manner described — see, for example, several papers by Briggs in the *Meteorological Magazine*.²⁻⁴ The problem of relating point to line rainfall rates has been investigated by using data from the Cardington⁵ and Winchcombe rain-gauge networks. In addition, communication engineers have established their own lines of rain-gauges near Mendlesham, Suffolk, where there are some 40 gauges along 8- and 16-km lines,⁶ and Ilkley Moor, Yorkshire, where there are 10 gauges along a 13-km path.⁷ Marine radars operating at a wavelength of 3 cm are used to interpolate the rainfall field between these gauges. Both these lines consist of specially developed rain-gauges⁸ which record 10-second rainfall totals.

Weather radars have been used for a number of years by the Meteorological Office but these do not provide quantitative data, nor is any permanent record kept. More recently a quantitative radar has been used regularly in North Wales for hydrometeorological research studies in the Dee Weather Radar Project.⁹ Quantitative data are also obtained occasionally by the Meteorological Research Unit at the Royal Radar Establishment at Malvern and the

Department of Electrical Engineering at the University of Birmingham. Other radars exist at various establishments, including one at the USAF base at Alconbury, Hunts. Data from all of these radars would be of some value in communication applications, in particular in deriving an approximate climatology of mesoscale precipitation. However, none is fully adequate for deriving detailed attenuation statistics. The situation would change if proposals for a quantitative weather-radar network consisting of 12 radars covering the United Kingdom come to fruition.¹⁰ This network would operate continuously and would provide qualitative coverage over the whole country and neighbouring sea areas, as an aid to forecasting precipitation, and quantitative coverage within about 75 km of each radar, to permit surface precipitation to be measured over areas of particular interest, for example, river catchments.

Conclusion. Several methods of estimating statistics of attenuation for communication links and diversity systems are in use. The most direct method is to make actual measurements but the data sample is limited and the equipment is seldom available. When a quantitative weather radar is available, attenuation statistics can be readily derived and a large data sample attained. In the absence of a quantitative radar system, use is made of data from existing or specially installed rain-gauges. This is the method adopted in the United Kingdom at present but the situation could change if quantitative radar data were available.

REFERENCES

1. STRICKLAND, J. I.; The measurement of slant path attenuation, using radar, radiometers, and a satellite beacon. Inter-Union Commission for Radio Meteorology. Colloquium on the Fine Scale Structure of Precipitation and Electromagnetic Propagation, Nice, October 1973, III-6.
2. BRIGGS, J.; Estimating the duration of high-intensity rainfall. *Met Mag, London*, **97**, 1968, pp. 289-293.
3. BRIGGS, J. and HARKER, J. A.; Estimates of the duration of short-period rainfall rates based on clock-hour values. *Met Mag, London*, **98**, 1969, pp. 246-252.
4. BRIGGS, J.; Probabilities of aircraft encounters with heavy rain. *Met Mag, London*, **101**, 1972, pp. 8-13.
5. HOLLAND, D. J.; The Cardington rainfall experiment. *Met Mag, London*, **96**, 1967, pp. 193-202.
6. TATTERSALL, R. L. O., BARNES, B. C. and CARTWRIGHT, R. E.; Multipath transmission tests at 11, 20 and 37 GHz. *IEE Conf Publ No. 98*, Propagation of radio waves at frequencies above 10 GHz. *London*, 1973, pp. 65-69.
7. WATSON, P. A., GOODALL, F. and ARBABI, M.; Linear cross polarization and attenuation measurements at 11 and 36 GHz. *IEE Conf Publ No. 98*, Propagation of radio waves at frequencies above 10 GHz. *London*, 1973, pp. 179-182.
8. NORBURY, J. R. and WHITE, W. J. K.; A rapid response rain-gauge. *J Phys, E, London*, 1971, pp. 601-602.
9. HARROLD, T. W., ENGLISH, E. J. and NICHOLASS, C. A.; The Dee Weather Radar Project: the measurement of area precipitation using radar. *Weather, London*, **28**, 1973, pp. 332-338.
10. Reading, Water Resources Board, Dee Weather Radar Project, Operations Systems Group. The use of a radar network for the measurement and quantitative forecasting of precipitation. Reading, 1973.

THE METEOROLOGICAL OFFICE Mk 5 WIND SYSTEM

By C. V. ELSE

Summary. Increasing requirements for large numbers of wind-direction and speed indicators at separated points on large airports, and for wind data suitable for further processing, have shown the existing Meteorological Office Mk 4 wind system to be inadequate under these conditions. Development was undertaken of a new wind system (Mk 5) designed to overcome these difficulties. The outputs of the new system are compatible with the telemetry required for longer data-transmission paths. The direction and speed values are scaled in a manner which makes them suitable for use with most data-processing systems. The number of display outlets is unlimited, and various ancillary devices are provided to produce the most commonly needed processed data, for example, wind components, mean values and gust detection. Sets of the new equipment have been installed at several places, including London/Heathrow Airport, where the system has been fully duplicated.

Introduction. In 1954, because of the limitations of the Dines pressure-tube anemometer in regard to remote and multiple displays, the Meteorological Office introduced electrical systems of wind measurement based on magstrip-type transmissions for wind-direction information, and a.c. generators for wind speed. These systems have been adequate in the past when the number of displays required has been modest, when there has been little need for further processing of the basic wind data, and when the cable distances between the sensing heads and the displays have been relatively short. As a result of recent demands for an increase in the number of displays, for these displays to be at greater distances from the sensing heads and sometimes widely separated from each other, and for the facility to process the basic wind data in various ways at the display points, limitations of the existing systems have become increasingly obvious and unacceptable.

The limitation of 10 ohms for the maximum resistance of the cables between the sensor and the wind-speed displays results in the use of extremely heavy and expensive cable when runs of 3–5 km are involved. Further, when these long runs are used the cable capacitance becomes important also. The standard Mk 4 cup-generator anemometer has an effective inductance of about 0.75 henry. This value, coupled with the capacity of the maximum specified lengths of cable, creates resonance in the system at the higher generated a.c. frequencies, and is liable in extreme circumstances to cause errors at wind speeds of 80–140 kt of over 10 per cent. This phenomenon is inherent in the design of the system.

There is also a 40-ohm limitation on the cable connecting the magstrips which form the transmission system for wind direction. Although cable capacitance is of little importance in this instance, the receiver magstrips used in the direction indicators have a marked resonance at about 4 Hz, which is excited by any fluctuations in wind direction at this frequency. This results in momentary anomalous indications on the dial.

The way in which the wind information is transmitted from the sensing heads to the displays, whilst adequate for the type of installation for which the systems were originally designed, does not lend itself to the further processing of the basic data for the meteorologist or air traffic controller. Such processing has therefore had to be done by human intervention, with all the limitations which such intervention implies.

Design criteria for the new system. As a result of the limitations listed above, of indications of the forms in which wind data are likely to be required

in the future, and of estimates of the increase in the number of displays likely to be required from a single measuring point, development was undertaken in 1969 of a new electronic wind-measuring system which would use the existing sensors but would have the following characteristics:

- (a) Compatibility with transmission of the data by telemetry, using either cable or radio links, over great distances (preferably unlimited).
- (b) Facilities to provide an unlimited number of displays.
- (c) Facilities for the generation of orthogonal wind components, with respect to any selected axes.
- (d) Facilities for the independent processing of the data in various ways at any point in the system.
- (e) Great reliability.
- (f) Low power consumption.
- (g) Facilities for setting up and checking the system for correct operation by reference to independent external electrical standards.
- (h) Facilities for the use of modified or different wind sensors, particularly wind-speed sensors with lower starting speeds.

The result of this development is the Meteorological Office Mk 5 wind system, which has now been introduced at London/Heathrow Airport. Whilst initially developed for use at civil airports and military aerodromes, it also offers facilities of interest in other fields, including:

- (a) The derivation of instantaneous or averaged values of wind speed and direction, or of cross-wind and along-wind components for any runway on a continuous basis.
- (b) The possibility of light-weight battery-powered equipment, capable of being dropped by parachute to transmit wind information by radio link from a remote site, or of being set up there.
- (c) The input of wind data, processed in any desired way, into a data-logger or directly into a computing system.
- (d) The provision of wind data in a form suitable for automatic extraction of gusts, deviation from mean values, Fourier analysis (within the limitations of the sensors and encoding systems) and similar processes.

Description of the components of the system

Wind direction. In order to ensure homogeneity (for climatological purposes) with earlier data, the Mk 5 system is designed to operate with the sensors used in the older electrical systems. However, there is no reason why new sensors should not be used with the same, or other, transducers to give similar results. The wind-direction transducer is a 2-in synchronous-link magstrip. In the present application (Figure 1) the three-phase stator winding is energized by a three-phase a.c. sinusoidal supply, which induces in the magstrip's rotor winding a single-phase sinusoidal waveform whose phase varies through 360 degrees, relative to a reference phase, as the rotor makes one complete revolution. From this variation in phase is generated a variable-width pulse waveform, which is processed* to give an output varying from 0 to 10 volts as the direction of the wind vane changes.

* The width-modulated pulses are processed by smoothing after the application of a d.c. clamp.

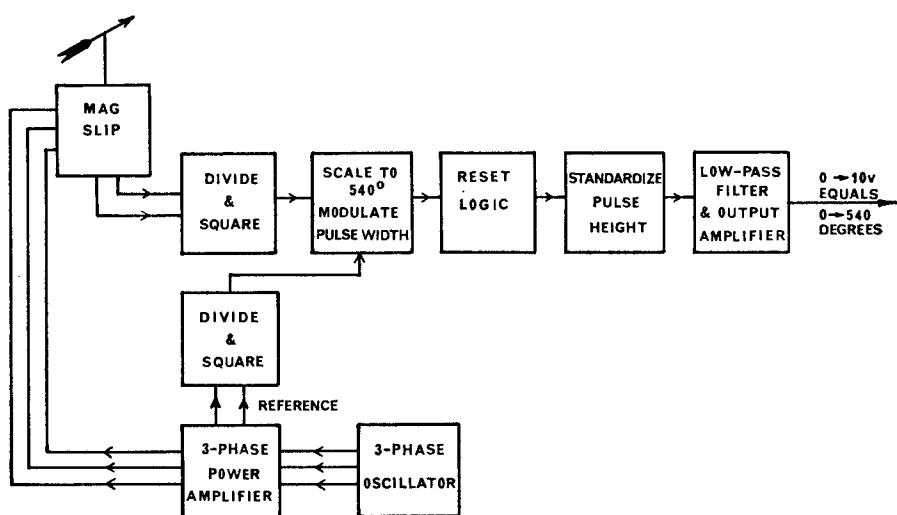


FIGURE 1 — BLOCK DIAGRAM OF WIND-DIRECTION ENCODING CIRCUITS

One of the major difficulties encountered in the design of telemetered wind-direction systems which use scales having fixed limits (as opposed to the circular compass-rose type of display which is continuous) is that, if the wind vane oscillates about the point corresponding to zero and full-scale output, the output is indeterminate since it varies rapidly between the two extremes. The wind-direction scale is therefore extended to cover a range of 0–540 degrees, and a small logic system is used to reset the scale deflexion from zero (or full scale) to a corresponding stable deflexion point at two-thirds (or one-third) of full scale respectively. Hence the scaling of the wind-direction indicator, shown in Plate I, is:

Direction (degrees)	090	180	270	360	090	180	270
a.c. signal (volts)	0.00	1.66	3.33	5.00	6.66	8.33	10.00

This scaling allows the 090-degrees (0-volt) deflexion to reset to the new stable position at 6.66 volts, and correspondingly permits the 270-degree (10-volt) deflexion to reset to 3.33 volts. It will be noted that the direction scale for this system starts at east and finishes at west. This is an arbitrary decision, since the scale could start at any convenient point. East was eventually chosen because it places north in the familiar position at top centre of the dial.

Wind speed. The wind-speed sensor is the standard Mk 4A three-cup anemometer, as in previous systems. This sensor is coupled to a transducer in the form of an a.c. generator. In the earlier systems, however, the output was the magnitude of the a.c. voltage produced by the generator, and this led to many problems. In order to obtain a sufficient output, a strong magnetic field was necessary and the resulting magnetic 'cogging' action led to a high starting speed (approximately 5 kt). In addition, the system was sensitive to the loading imposed by the displays, and this had to be kept constant by substituting

dummy loads. The number of displays was limited to six, and the system's accuracy was affected by the resistance and capacitance of the connecting cable between the generator and the displays. Because the a.c. voltage had to be rectified for use in the displays, the chart scale was also highly non-linear below about 10 kt, and this resulted in very poor resolution of wind speeds below this figure.

In the Mk 5 system the same generator is used, but the analogue of the required wind-speed information is now the frequency of the generated a.c. voltage. This has freed the system from the previous restrictions. The resistance of the connecting cables ceases to be important. Furthermore, since the magnitude of the generated voltage is no longer of interest, the magnetic cogging action has been minimized by increasing the rotor-stator air gap. This has resulted in a lowering of the starting speed of the assembly to less than 2 kt. The chart scale is now substantially linear from starting speed upwards; this gives greatly enhanced resolution at low speeds.

The relationship between wind speed and rotational speed of the cup-generator anemometer is such that the output frequency increases by almost exactly one hertz per knot of wind speed. For each cycle of the generated frequency, two pulses of accurately known width and amplitude are produced in a conventional frequency-to-voltage converter (Figure 2). These pulses are

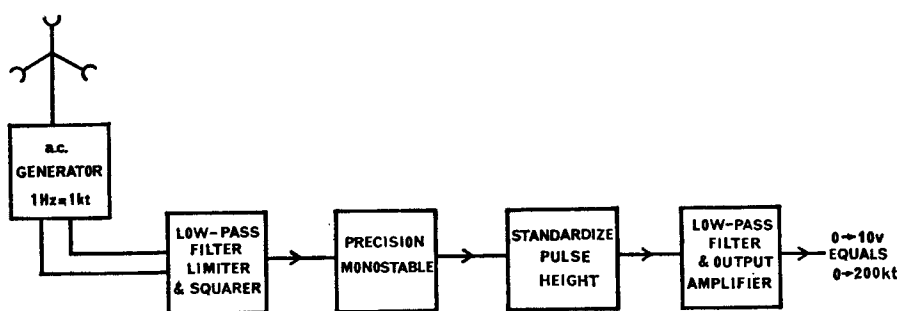


FIGURE 2 — BLOCK DIAGRAM OF WIND-SPEED ENCODING CIRCUITS

then processed* to yield an output voltage so scaled that 0-200 kt are represented by 0-10 volts. In the normal displays (Plate II) only wind speeds up to 100 kt are displayed, using a scale of 0-5 volts. At stations where high wind speeds may be encountered, a special range-doubling unit is available to alter the display maximum to 200 kt, using the full scale of 0-10 volts. This unit operates when the wind speed reaches a predetermined level in the range 70-90 kt. Once the scale-doubling action has occurred, it is locked in and a warning signal is displayed, resetting of the scale to the normal state being made manually as in the present Mk 4 system. Alteration of wind-speed scaling is effected locally, and need not apply to all indicators or recorders. The data being transmitted are *always* scaled on the basis that 0-10 volts represents 0-200 kt.

* The time-modulated pulses are processed by smoothing after the application of a d.c. clamp.

Display and telemetry. Any number of displays can be used, both locally and remotely. The data are displayed on suitably scaled conventional meters, or recorded on potentiometric or galvanometric recorders. A special servo-driven wind-direction indicator (Plate III) which converts the wind-direction information into the form of a 360-degree compass-rose display is available for locations (such as air traffic control centres) where the meter type of display is considered unsuitable. Electronic units at the outlet points are capable of supplying up to 50 displays of any type except galvanometric recorders. The high current requirement of these recorders limits the number which can be attached to a single electronic unit to 10. Figure 3 shows the schematic arrangement of the basic Mk 5 wind system on the sensor side of the telemetry link. Other display facilities can be specially arranged, and various forms of data processing are available. Some of the latter are available as standard options and are discussed below in the section on processed data.

The analogue telemetry system used with this equipment has been introduced by the Operational Instrumentation Branch of the Meteorological Office as standard for general use. The system has a resolution of 0.1 per cent, and an accuracy not worse than ± 0.2 per cent over a wide temperature range. Chosen for reliability, it uses internationally agreed carrier frequencies, and encodes the data on to the carriers by frequency shift keying. The Mk 5 system uses two analogue channels to transmit continuous wind-speed and direction data, but the same modulation and demodulation units (modems) could be used for 50-baud digital transmission if required. The modems are approved by the Post Office for connection to public lines in the United Kingdom. On lines using repeater amplifiers the transmission distance is unlimited, otherwise the distance is limited to that which gives a transmission loss of about 46 decibels at the carrier frequency in use. Typically, this distance would be about 80 km. Figures 4 and 5 show typical arrangements of units to meet local and remote telemetered applications.

Telemetry is not essential to the basic operation of the Mk 5 system. It is only needed when displays are required at a great distance from the sensors, or when the route from the sensors to the displays precludes the economic installation of short lines. Without the telemetry option, the sensors can be linked by cable to the processing unit over distances up to about 3 km, and the processing unit can be linked by cable to the displays up to a distance of about 1 km (a loop resistance of about 100 ohms).

Information processing. The basic meteorological information produced by the sensor-transducer combinations is transmitted in an unprocessed state to the receiving points. In this form it contains all the information which the sensors are capable of providing, and is not degraded in any way. For many purposes, however, the data require to be processed in varying ways. The versatility of the Mk 5 system is such that it can present the data processed in different ways at different displays. Probably the most useful processing method used is that of time-averaging, to give displays of wind speeds averaged over various lengths of time (e.g. a 10-minute mean wind for meteorological reporting, or a two-minute running-mean wind for air traffic control use). Other facilities now available provide running means of wind direction. The circuits used for this purpose are capable of dealing with the discontinuities generated when the reset logic system of the direction encoder removes the scale deflexion from its

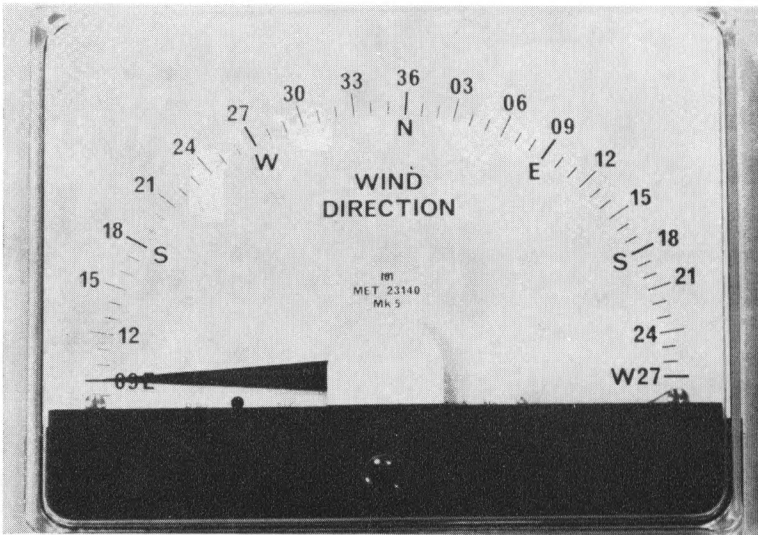


PLATE I — 180-DEGREE WIND-DIRECTION DIAL (NORMAL METER TYPE)
See page 130.

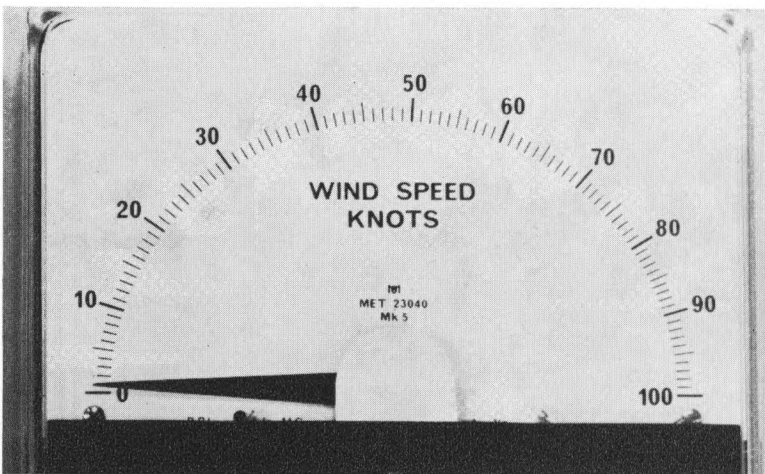


PLATE II — 180-DEGREE WIND-SPEED DIAL (NORMAL METER TYPE)

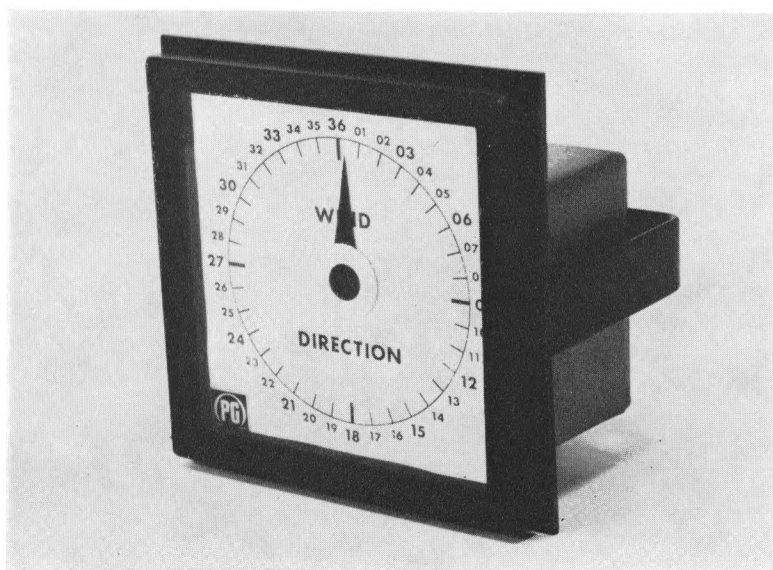


PLATE III — AIR TRAFFIC CONTROL 360-DEGREE COMPASS-TYPE WIND-DIRECTION DIAL

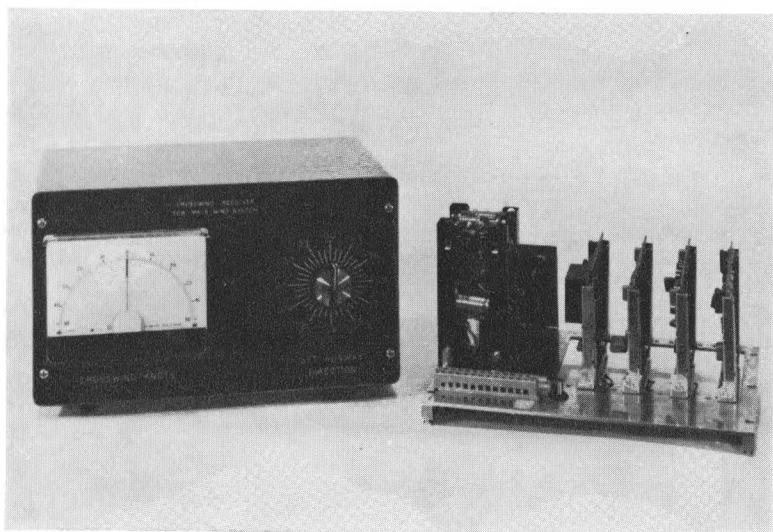


PLATE IV — MK 5 SYSTEM CROSS-WIND RESOLVER

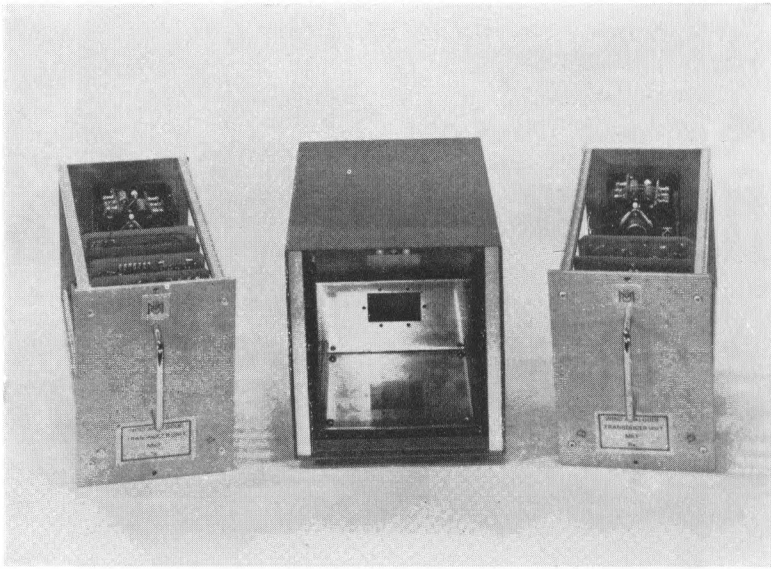


PLATE V — FREE-STANDING ENCODER AND DECODER UNITS, WITH CASE

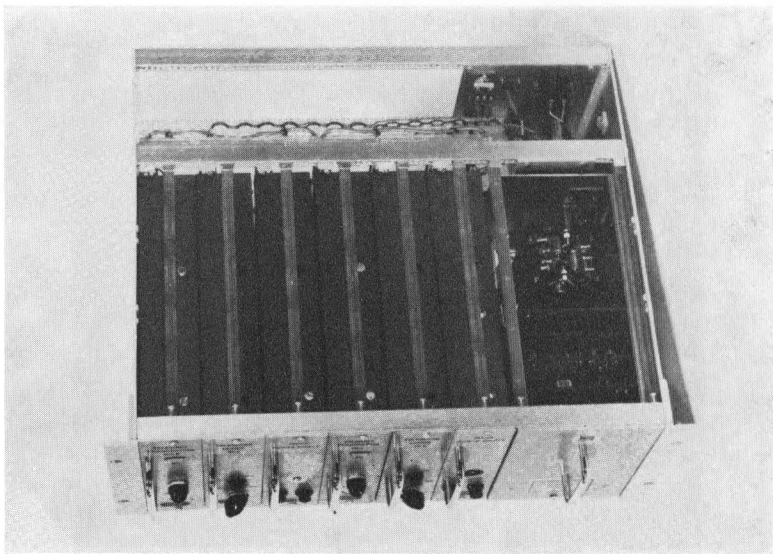


PLATE VI — TELEMETRY TRANSMITTER UNIT UNCASD, FOR 19-IN RACK MOUNTING

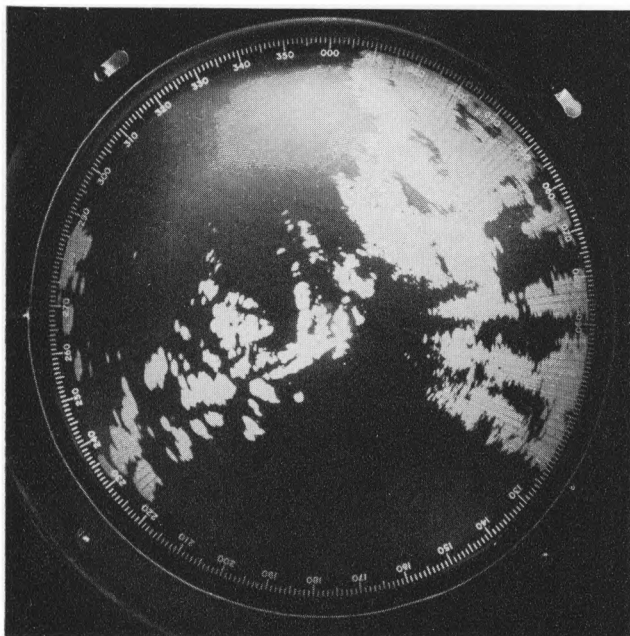


PLATE VII — GROUND CLUTTER OBSERVED BY TYPE 43S RADAR AT LLANDEGLA
WHEN THE BEAM AXIS WAS AT AN ELEVATION OF 0.5°
See page 140. The outer range is 50 kilometres.

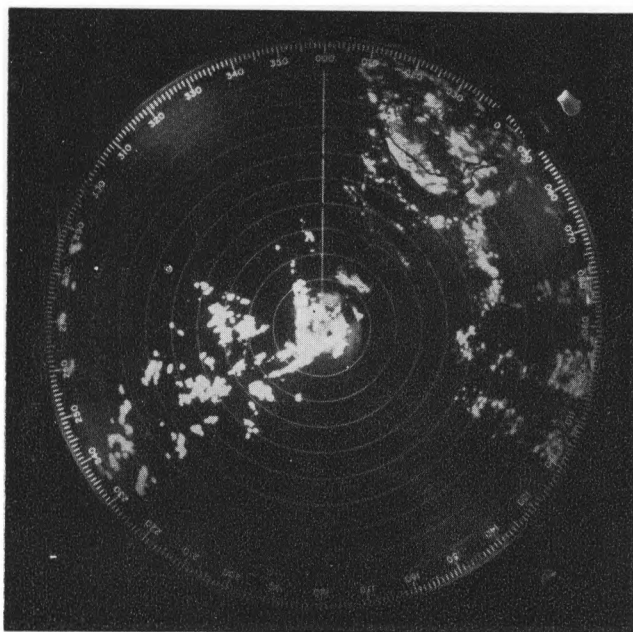


PLATE VIII — AS PLATE VII, EXCEPT THAT THE RADAR BEAM WIDTH HAS BEEN
NARROWED
The coastline of North Wales and Lancashire is also shown.

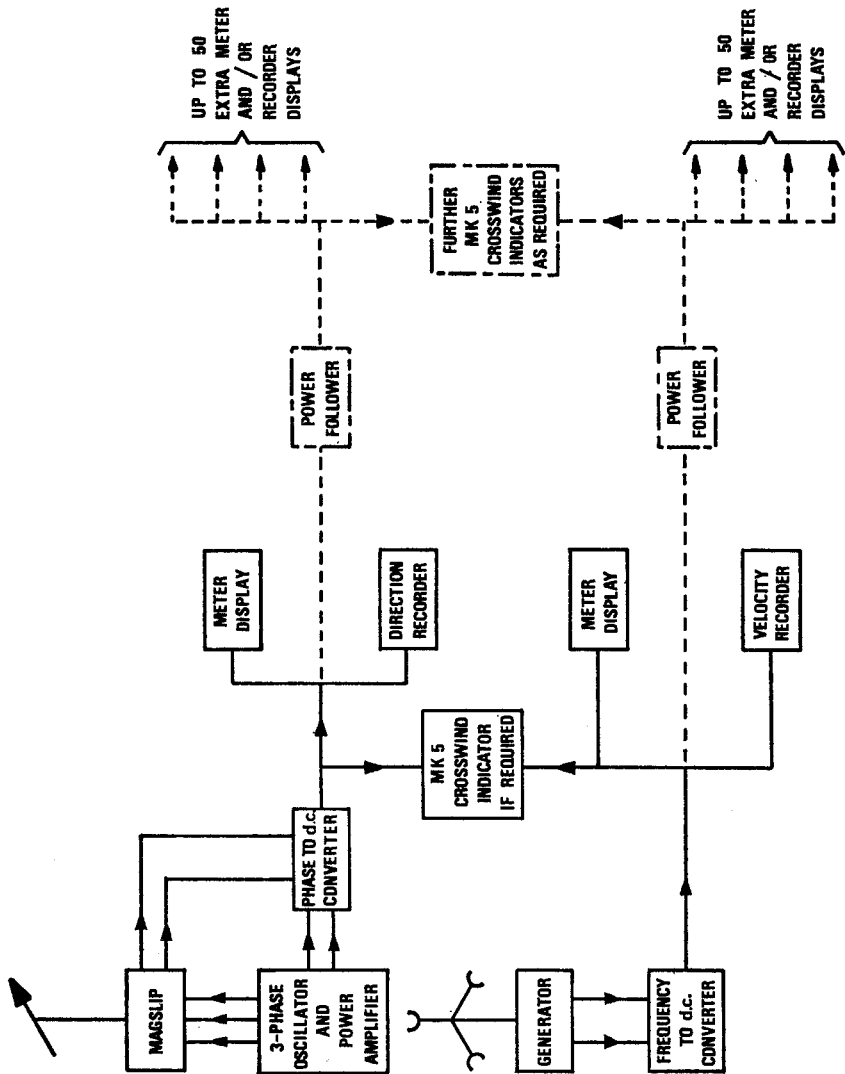


FIGURE 3 — BLOCK DIAGRAM OF BASIC LOCAL MK 5 WIND SYSTEM

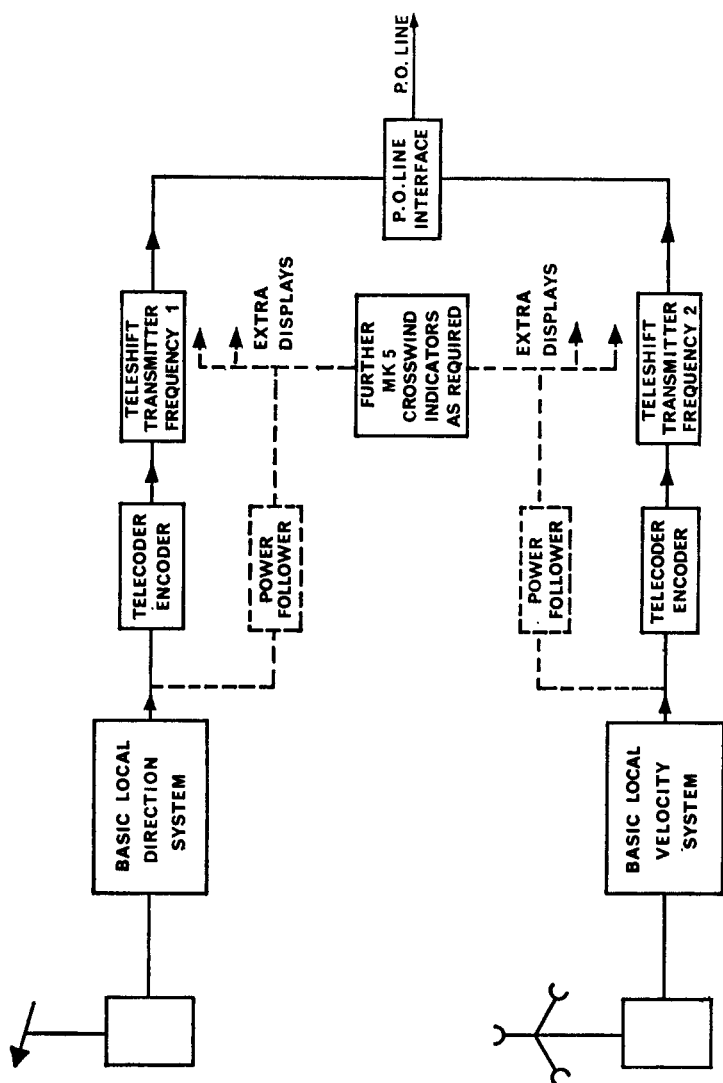


FIGURE 4 — BLOCK DIAGRAM OF BASIC TELEMETERED MK 5 SYSTEM (TRANSMITTER END)

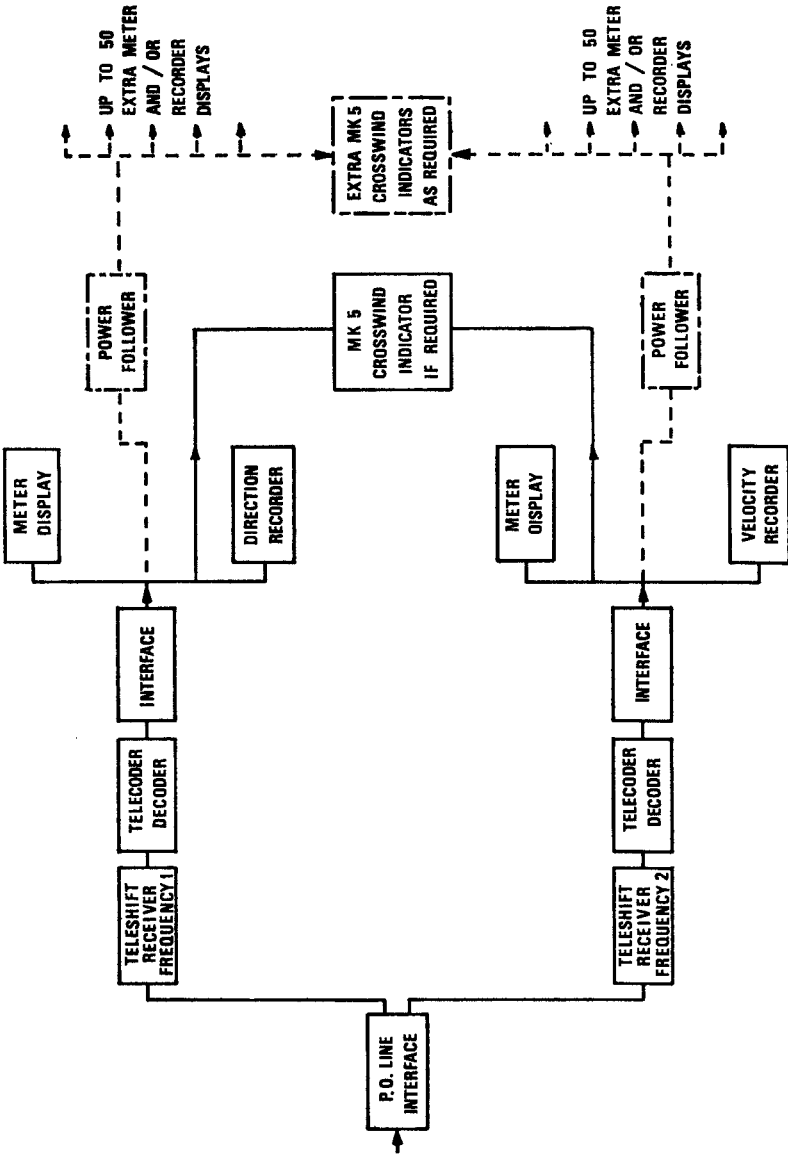


FIGURE 5 — BLOCK DIAGRAM OF BASIC TELEMETERED MK 5 SYSTEM (RECEIVER END)

extreme positions, and can generate their own independent scale switching when their outputs reach the scale extremes. These direction-averaging circuits are also capable of changing the 540-degree scale to a 360-degree scale and vice versa.

Facilities are also available to detect and indicate the value of the maximum gust, either in a fixed time period (e.g. maximum gust in each hour) or in a constantly moving time period (e.g. maximum gust in the previous 10 minutes counting from the present time), and to derive the number of times gusts exceed the mean wind speed by a certain value or percentage. Similar facilities (e.g. maximum deviation from mean) are available in relation to wind direction.

A requirement in any general-purpose system of this kind is the facility to produce orthogonal components, especially with respect to *any* selected axis; for example, to measure the winds blowing across or along a selected path. An instrument (Plate IV) to perform this task is already available as a part of the Mk 5 system, and is an all-electronic counterpart of the cross-wind resolver shortly coming into service with the Mk 4 wind system. The 10-volt linear scale representing 540 degrees in direction is first corrected for deviation of axes from north, and for magnetic deviation if required, by algebraically adding voltages representing the required corrections. The resultant is split into two compatible voltage scales of 0–360 degrees and 0–180 degrees, which are further separated into voltages representing 90-degree quadrants, each with a signal giving the appropriate sign (positive or negative). The linear voltage representing a given quadrant is then converted to a sine function and multiplied by the instantaneous value of the wind speed. The output, which represents the value of the required orthogonal component, is displayed on a centre-zero meter, the direction of deflexion being determined by the quadrant sign (positive or negative) derived earlier. The analogue output from this device is again available for further processing if required.

Construction and electronics. The basic constructional techniques which have been adopted as standard in all new instruments and systems developed in the Operational Instrumentation Branch of the Meteorological Office are based on the International Telephone and Telegraph Corporation Standard Equipment Practice (ISEP) system. Individual parts of the circuitry are broken down into conveniently sized packages and mounted on small plug-in cards. Assemblies of cards are mounted into larger modules (or sub-units) which in turn plug together in sub-racks. The sub-racks either fit together into complete 19-in rack assemblies, where the equipment is large and complex, or fit into 19-in instrument cases to provide a finished assembly when the equipment is relatively small and compact. Views of different types of finished assemblies are shown in Plates V and VI. This method of assembly allows rapid fault-finding and repair by exchange of cards or modules in the field, whilst also giving great flexibility for altering or extending the capability of a system by adding plug-in cards for various purposes.

To ease maintenance and spares stocking, the components used are chosen from a restricted list of approved parts for which military-quality alternatives are available. Because of careful screening of components used, and the constructional techniques employed, which include the duplication of connections to all circuit cards, the reliability of the equipment will be high. Some sets of the telemetry equipment have now been in use for more than two years without

any failures, and equipment sub-units have been run for more than a year without any failures. The various circuits have all been found to operate correctly throughout the temperature range -20° to $+60^{\circ}$ Celsius.

Conclusion. Design of the Mk 5 wind system commenced in 1969 and prototype development was completed in one year. Since then the system has been undergoing field trials, user-evaluation trials, and production engineering. As a result of trials using a specially made sensor in which a single wind vane drove both Mk 4 and Mk 5 transducers, carried out in conjunction with the Observational Requirements and Practices Branch of the Meteorological Office, it has been shown that the accuracy and performance of the Mk 5 system is at least equal to that of the Mk 4 system. In fact, in view of the known deficiencies of the Mk 4 system, it is likely that most of the small discrepancies between the two systems should be ascribed to errors in the older system.

The basic Mk 5 system is now available for production, and most of the ancillary facilities referred to in the text are approaching this stage. An example of this equipment is in routine operational use for relaying wind information from Beaufort Park to the main Headquarters Building in Bracknell, as part of the CARD (Continuous Automatic Remote Display) system.* This particular installation provides analogue chart records in the Central Forecasting Office, and digital displays in the main entrance hall some 350 m away.

The most important installation has recently been made at London/Heathrow Airport, where the number of displays required could no longer be supported by the existing Mk 4 system. This installation comprises three full sets of Mk 5 receiving equipment and two sets of transmitting equipment, interlinked in such a way that failure of any part of the equipment will not deprive the airport of wind information. As a further precaution, the various parts of the equipment are connected to the airport emergency power grid, and the sensors themselves are duplicated, as also are the Post Office lines used for the telemetry links from the processing unit to the displays.

Other installations are in the course of planning. Installation of a system at Stornoway Airport is about to start, and it is possible that the National Institute of Oceanographical Sciences will use one of these equipments on their research ship *Discovery*. Another set is being used by the Royal Armaments Research and Development Establishment at Fort Halstead, in conjunction with a digital data-logger, and the Royal Aircraft Establishments at Bedford and Aberporth are installing sets. A second CARD system is being used for the telemetry of wind data from the Post Office Tower to the London Weather Centre. Telemetry of other data will be added to this system shortly.

The Mk 5 wind system represents one of the first of the new generation of instruments now coming into service in the Meteorological Office. It is based on the newer technologies, using integrated circuits and digital techniques in addition to analogue processes. It is modular in concept, which allows systems to be expanded (or contracted) to meet the particular requirements of each installation. The construction allows maintenance and repair by replacement of individual cards or modules, and the general design philosophy is such that electronics failures should be reduced to a negligible level.

* SANDS, K. J. T. and WILKINSON, D.G.; The meteorological transmission system operating between Beaufort Park and Meteorological Office Headquarters. *Met Mag, London*, 103, 1974, pp. 74-81.

Acknowledgements. Acknowledgement is made of the efforts of the team who have been engaged in this development, in particular Mr D. Painting, upon whose original work the wind-direction processing circuits are based, and Mr D. G. Wilkinson, who was responsible for the production engineering of the system.

551.501.8: 551.577

GROUND CLUTTER OBSERVED IN THE DEE WEATHER RADAR PROJECT

By T. W. HARROLD

Anyone who has viewed a weather-radar display is aware that echo from precipitation is difficult to detect in some localities because echo from the ground, buildings, trees etc., termed ground clutter or permanent echo, is also present. This clutter can be reduced by elevating the radar beam so that less energy strikes the ground, but then the precipitation in the beam may not be representative of that reaching the ground. At long ranges the beam may even be above the precipitation. In making quantitative estimates of the precipitation at the surface it is particularly important that the beam should be set at as low an angle as possible, which is usually about 0.5° , and ground clutter cannot be completely avoided. It can be minimized by careful siting of the radar and by using a narrow radar beam.

In the Dee Weather Radar Project¹ a standard Plessey Type 43S weather radar at Llandegla was used to measure the rain falling on to sub-catchments of the River Dee. This radar has a beam width to half-power points of 2° . Plate VII shows the extent of ground clutter observed. Over the Dee Valley, to the south-west of the radar, the echo was broken, and it was found possible to extrapolate rainfall estimates across individual echoes, but to the north-east the echo was continuous and rainfall measurements were not possible. The conventional definition of beam width means that half of the total energy radiated is within a 2-degree cone. However, when considering the extent of ground clutter it is necessary to consider also the energy outside the cone. For instance, north-east of the radar the land is at an elevation of about -1° , or 1.5° off the beam axis, and therefore outside the half-power points. The incident radiation was about 10 dB (a factor of 10) below that at the beam axis but this was sufficient to result in the echo shown. A further problem with the 43S radar was that the melting layer (bright band) was frequently within the beam in winter, which lessened the accuracy of the estimates of surface rainfall.

Because of these difficulties the beam width as defined by the half-power points has been reduced to 1° . This has been accomplished by changing the radar wavelength from S-band (10 cm) to C-band (5.6 cm) whilst retaining the same aerial (the alternative of increasing the aerial size would have been much more costly). When the beam axis is at an elevation of 0.5° the melting layer is now intersected within a range of 50 km when it is less than 1350 m above sea level instead of 1800 m. The ground clutter now observed is shown in Plate VIII. The overall sensitivity of the radar is very similar to that of the 43S, and the reduction in clutter compared with Plate VII has been obtained by narrowing the beam and also by improving the profile of the lower portion

of the beam. The power density 1.5° below the beam axis is about 30 dB (a thousandfold) less than at the beam axis. Measurements of surface rainfall are now possible north-east of the radar.

During the latter part of 1974 the radar is to be converted into a real-time system, centred around a Digital Equipment Corporation PDP 11-40 mini-computer, using software being developed by a team at the Royal Radar Establishment.² This software includes provision for the extrapolation of rain echo into a region of ground clutter so that the display available to any user of the data will be free of this clutter.

REFERENCES

1. HARROLD, T. W., ENGLISH, E. J. and NICHOLASS, G. A.; The accuracy of radar-derived rainfall measurements in hilly terrain. To be published in the July 1974 issue of the *Quarterly Journal of the Royal Meteorological Society*, London.
2. TAYLOR, B. C.; The development of a prototype system for the processing, transmission and remote display of data from a weather radar. Malvern, Royal Radar Establishment, 1974. (Unpublished, copy available in the Meteorological Office Library, Bracknell, Berks.)

551.551.2:634.0

WIND-SPEED MODIFICATION BY A VERY ROUGH SURFACE

By H. R. OLIVER

(Institute of Hydrology, Wallingford)

Summary. Wind speeds were measured over Thetford Chase with a standard anemograph and sensitive anemometers on three very windy days. It is shown to be possible to obtain from the anemograph traces values for average speeds and maximum gusts reduced to the standard meteorological height of 10 m above the 'surface'.

Data for Thetford were compared with results for Meteorological Office stations in or near the East Anglia region. It was found that the hourly average speeds measured over the forest were only about 60 per cent of those measured at the nearby stations. The reduction in gust magnitudes — of obvious importance to forest damage problems — was not so large. The gust/mean ratio for the forest was found to be about 2.0 — a value typical of urban areas — in comparison with an average value of less than 1.6 for the other stations.

It is possible to estimate winds above a forest from measurements made elsewhere so long as the calibration constant between the sites can be measured or estimated.

Introduction. The Institute of Hydrology is carrying out an extensive research project, the object of which is to investigate the meteorological factors concerned with the evaporation process from a forest. The site is in Thetford Chase, which is a large fairly flat area mainly planted with a mixture of Scots and Corsican pine. The trees within half a kilometre of the site are all Scots pine with a mean height of about $16\frac{1}{2}$ m.

On 2 April 1973 a severe gale occurred and some damage to the forest resulted. The equipment was operated during the gale to obtain wind-profile data; sensitive Casella anemometers were mounted at 11 levels within and above the canopy and there was also an anemograph trace of the output from a standard Meteorological Office cup generator anemometer Mk 4. A paper describing the micrometeorological and forestry results is being published (Oliver and Mayhead¹) but of particular interest here is a comparison of results obtained over Thetford Chase with anemograph data from elsewhere in East Anglia. Two further days with strong but less severe winds which have occurred whilst the full equipment was being operated have also been investigated.

Data on the effects of gales upon forested and other areas have obvious relevance to several planning problems. It is also useful to be able to estimate wind speeds above a forest by using only measurements made elsewhere.

Theoretical considerations

(a) *Effect of surface roughness on wind-profile shapes.* The wind profile above a surface can be expressed in the standard logarithmic form

$$u = \frac{u_*}{k} \ln \left(\frac{z}{z_0} \right), \quad \dots (1)$$

where u_* is the friction velocity, k is von Kármán's constant and z_0 is the roughness length. This equation can be used for any surface provided that the height z is that above the zero-plane displacement, d ,[†] rather than above the ground surface. For short vegetation such as grass the effect of d can safely be neglected; for taller vegetation a value of d of 75 per cent of crop height may be used in the absence of actual data. The simple logarithmic equation applies for neutral conditions. For the strong-wind conditions on the days under investigation here the stability was indeed near-neutral. The Richardson number (the most commonly used stability function), which is expressed as

$$Ri = \frac{g}{T} \frac{\partial \theta / \partial z}{(\partial u / \partial z)^2},$$

tends to zero for high wind speeds because the denominator contains the square of the wind-speed gradient.

For two surfaces with roughness lengths $z_{0,1}$ and $z_{0,2}$ the relationship between the speeds measured at heights z_1 and z_2 above the crop zero-plane displacements can be shown to be given by the relation:

$$u_1 = u_2 \left(\frac{\ln (z_1 / z_{0,1})}{\ln (z_2 / z_{0,2})} \right). \quad \dots (2)$$

This equation shows that it is only at very great distances above the surface that the effect of roughness length becomes negligible and the profiles merge (see Figure 1).

Hence the mean wind speed measured at a certain height above d for a rough surface (large z_0) will be considerably less than the mean speed measured at the same height above a grass surface (small z_0 , negligible d); from purely theoretical considerations the overall severity of a gale will therefore be reduced at levels close to a surface with a large roughness length, be it a forest or city.

(b) *Effect of surface roughness on gust sizes.* The previous discussion applies to mean wind speeds and profiles — certainly not to those obtained by averaging over periods shorter than five minutes. Detailed analyses of anemograph records have shown that gust strengths are not so much reduced by surface roughness effect (Shellard²). It is a consequence of this that the ratio of maximum gust to mean wind speed must increase with surface roughness. There is considerable variation in this ratio between various gale events but it has been suggested (Hardman *et alii*³) that gust/mean-wind ratios can be taken as 1.5, 1.7, 1.9 and 2.1, corresponding to the four terrain classes ranging from open level unobstructed country to very rough surfaces such as cities.

Analysis of results. The wind-speed data obtained at Thetford on 2 April 1973 were by far the highest speeds that had occurred while detailed measurements were being made. The maximum gusts recorded by the anemograph were also the highest that had ever been obtained in the five years during which

[†] If the simple logarithmic profile is extrapolated into a crop canopy the wind speed reduces to zero at a height of $(d+z_0)$ above the ground surface.

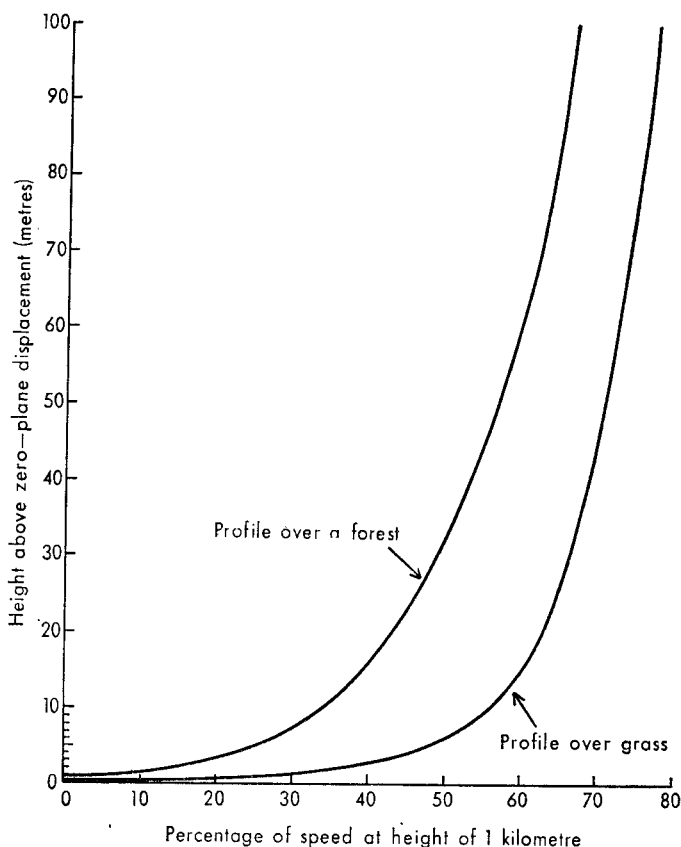


FIGURE 1 — COMPARISON OF THEORETICAL WIND PROFILES ABOVE GRASS AND ABOVE A FOREST, ASSUMING IDENTICAL WIND SPEEDS AT A HEIGHT OF 1 km ABOVE THE SURFACE

Roughness lengths of 0.03 m and 1.0 m have been used in the calculation of the profiles to give results comparable with the data presented in the paper.

the standard anemometer had been operating. There are four anemograph stations in or near the East Anglia region (Bedford, Cranwell, Marham and Coltishall) for which gale return-period analyses have been carried out and for which data are still being recorded (Hardman *et alii*³). The measurements obtained at these stations suggest that the general level of the gale in East Anglia had a return period approaching 10 years. The gale was so severe that many of the sensitive polystyrene anemometer rotors used in the measurement of wind profiles were damaged. However, whilst the rotors were still intact during the early part of the gale, analysis has verified that the wind profile above the forest did indeed follow a pure logarithmic form with a roughness length of about 1 m and a zero-plane displacement of 12 m. Analysis of the profiles obtained on the other occasions produced similar results which are in agreement with those found for more normal wind-speed conditions (Oliver⁴).

The standard height for anemograph data is 10 m above the 'surface'; for

a rough surface such as a forest this is equivalent to 10 m above the zero-plane displacement. For Thetford, therefore, the standard height is 22 m above the ground. The wind speeds at the anemograph sensor height of 31 m and the shape of the wind profile above the forest being known, it is possible to calculate the speed at any other height. The speeds for the standard height of 22 m are obtained by multiplying the speeds at 31 m by a factor of 0.79, and the data presented have been determined in this way.

The results obtained at Thetford and the published data from the Meteorological Office stations in or near East Anglia are given in Table I. It can be seen that there is a very large reduction in hourly average wind speeds measured over the forest in comparison with the other stations but that the reduction in gust size is not so great. There are of course considerable variations in the absolute values obtained at the various sites owing to their geographical separation. For some of the sites the effective sensor height is also not equal to the standard 10 m but the differences between these speeds and those at the standard height will not exceed 5 per cent.

Discussion. The very considerable reduction in wind speed over a forest in comparison with measurements made elsewhere has been clearly demonstrated; a much smaller reduction in gust magnitudes has also been shown. These results are of importance to anyone concerned with forestry or with the erection of structures within a forested area. The gust/mean ratio for Thetford Chase constantly takes the value of about 2, which is the same ratio as would be expected for an urban area with many large buildings (Hardman *et alii*³). The gust/mean ratios for the anemograph stations mostly lie within the range 1.5–1.7, which is what one expects for fairly open country.

The problem of forecasting or estimating maximum mean speeds for a given area of rough terrain from wind data obtained outside the area can be solved if wind-speed measurements are available covering the same period for both areas. It is then possible to obtain a calibration factor between the measurements at the two sites. For average speeds over Thetford Chase this factor has been shown to be about 1.6 or 1.7 in relation to the nearest Meteorological Office stations. Actual measurements from both sites also make it possible for equation (2) to be used to obtain an effective z_0 for the Meteorological Office station if z_0 for the forest can be measured or estimated. This equation can then be used to calculate the average speed at *any* level above the canopy from one value of average wind speed made at *any* level at the meteorological observing station. The maximum gust to be expected for any gale event is equal to about twice the calculated hourly average speed.

Acknowledgement. This paper is published by permission of the Director, Institute of Hydrology.

REFERENCES

1. OLIVER, H. R. and MAYHEAD, G. J.; Wind measurements in a pine forest during a destructive gale. Submitted to *Forestry*, London, 1974.
2. SHELLARD, H. C.; Extreme wind speeds over the United Kingdom for periods ending 1963. London, Meteorological Office, 1965. (Unpublished, copy available in Meteorological Office Library, Bracknell, Berks.)
3. HARDMAN, CAROL E., HELLIWELL, N. C. and HOPKINS, J. S.; Extreme winds over the United Kingdom for periods ending 1971. London, Meteorological Office, 1973. (Unpublished, copy available in Meteorological Office Library, Bracknell, Berks.)
4. OLIVER, H. R.; Wind profiles in and above a forest canopy. *QJR Met Soc, London*, 97, 1971, pp. 548–553.

TABLE 1 — ANEMOGRAPH DATA FOR THREE DAYS WITH STRONG WINDS

Anemograph site	Effective height metres	Maximum hourly wind speed m/s			Ratio to value for Thetford			Maximum gust m/s			Ratio to value for Thetford			Ratio of gust to hourly average		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
THETFORD	10	11	9	7½				22	19	15				2.0	2.1	2.0
Cranwell	13	19	16½	13½	1.7	1.8	1.8	28	25	21	1.3	1.3	1.4	1.5	1.5	1.6
Wittering	10	14½		10½	1.3		1.4	24½		14½	1.1		1.0	1.7		1.4
Bedford	9	20½		11½	1.9		1.5	34		18	1.5		1.2	1.7		1.6
Stansted	10	14½			1.3			26			1.2			1.8		
Wattisham	10	21½	15½	10½	2.0	1.7	1.4	32½	22	15½	1.5	1.2	1.0	1.5	1.4	1.5
Honington	13	18		11	1.6			29		17	1.3		1.1	1.6		1.5
Coltishall	10	19	13	11	1.7	1.4	1.5	32½	20½	17	1.5	1.1	1.1	1.7	1.6	1.5
West Raynham	14	19½	16½		1.8	1.8	1.5	34	24		1.5		1.5	1.7		1.5
Marham	10	19	14	12½	1.7	1.6	1.7	29½	22	18½	1.3	1.2	1.2	1.6	1.6	1.5

1 = 2 April 1973 2 = 26 May 1972 3 = 28 August 1971.

Data for Cranwell-Marham inclusive extracted from appropriate issues of the *Monthly Weather Report*, HMSO, London.

551.515.527:551.577.21(213)

THE MAGNITUDE OF HORIZONTAL DIVERGENCE AND VERTICAL MOTION ASSOCIATED WITH UPPER TROPOSPHERIC DISTURBANCES OF THE EQUATORIAL ATMOSPHERE

By F. E. LUMB

(Regional Meteorological Training Centre, Lagos, Nigeria)

Summary. It is shown that the changes of contour pattern from Duct to Bridge and from Duct to Drift in the upper troposphere can raise the top of the moist layer of the equatorial atmosphere by 150–200 mb over a period of three to four days, with important effects on the weather.

Introduction. It has been explained* how horizontal divergence can occur in the upper troposphere near and at the Equator when the contour pattern is changing from Duct to Bridge or from Duct to Drift. It remains to assess the magnitude of the divergence and the associated vertical motion.

Change from Duct to Bridge. If V_{ag} is the ageostrophic wind,

$$V_{ag} = k \times \frac{1}{f} \frac{dV}{dt},$$

where V is the horizontal wind, f the Coriolis parameter and k unit vertical vector.

Hence during the gradual change from Duct to Bridge, if parcels of air at latitudes 5°N and 5°S are experiencing an acceleration towards east of magnitude 5 m/s per day, which is by no means improbable at 300 and 200 mb, the magnitude of V_{ag} is found from the above equation to be 4.6 m/s. The direction of V_{ag} is towards north in the northern hemisphere, and towards south in the southern hemisphere, and the resulting mean horizontal divergence between 5°N and 5°S is $0.8 \times 10^{-5} \text{ s}^{-1}$.

Typically the change from Duct to Bridge affects only the upper one-third of the troposphere by mass (400–100 mb). Hence if there is simple tropospheric compensation and a mean upper divergence of $0.4 \times 10^{-5} \text{ s}^{-1}$ is assumed, this would be balanced by mean convergence of $0.2 \times 10^{-5} \text{ s}^{-1}$ up to 400 mb. It follows from the equation of continuity that ω ($= dp/dt$) at 400 mb is $-(1.2 \times 10^{-3}) \text{ mb/s}$, or 2 cm/s.

This rate of upward motion is small compared with that associated with deepening lows of middle latitudes, but the change from Duct to Bridge is usually a slow process lasting three or four days. Taking a mean value of ω in the lower troposphere as $-(0.6 \times 10^{-3}) \text{ mb/s}$, upward motion would amount to 50 mb a day, so that the total decrease of pressure following the motion during the change of contour pattern would be 150–200 mb. This would raise the upper level of the moist layer, which characteristically is between 750 and 700 mb in the equatorial trough, to 550 mb, and the depth of the moist layer would be doubled from 2.5 to 5 km.

A useful forecasting guide well known to meteorologists practising in East Africa is to expect thunderstorms when the top of the moist layer reaches beyond the 0°C level, which is almost invariably between 600 and 550 mb.

* LUMB, F. E.; Upper tropospheric disturbances of the equatorial atmosphere and their influence on rainfall near the equator. *Met Mag, London*, 102, 1973, pp. 269–272.

The above calculations show that the upper divergence associated with the change from Duct to Bridge over a period of three to four days is sufficient to raise the top of the moist layer above the 0°C level.

Change from Duct to Drift. Divergence caused by transequatorial flow accelerating down the pressure gradient is given essentially by $\partial V/\partial s$, the change of wind speed per unit distance along the streamline. An increase of speed by 5 m/s over a distance measured along the streamline equivalent to 5° of latitude is not exceptional at 300 and 200 mb. This corresponds to a horizontal divergence of $0.9 \times 10^{-5} \text{ s}^{-1}$, which is nearly the same as that calculated above for the change from Duct to Bridge. Hence similar changes in the depth of the moist layer and in the weather can be expected, if the Drift pattern develops and persists over a period of three to four days.

Changes from Bridge or Drift back to Duct. For the reverse changes, upper convergence replaces upper divergence, with consequent marked reduction of rainfall, both in extent and in amount per unit area, within a period of 24–48 hours.

INSTITUTE OF PHYSICS AWARDS TO THE DIRECTOR-GENERAL

Dr B. J. Mason, C.B., F.R.S., Director-General of the Meteorological Office, has been awarded the Glazebrook Medal and Prize by the Institute of Physics 'for his contributions to numerical methods of weather forecasting by computer and for his success in encouraging the scientific spirit within the Meteorological Office'.

The Medal and Prize were awarded at the Annual Dinner of the Institute on 7 May 1974.

NOTES AND NEWS

METEOROLOGICAL OFFICE WEATHER OBSERVING SYSTEMS

Ten Meteorological Office Weather Observing Systems (MOWOS) Mk 2 have been obtained for operational evaluation. Three have been installed at Beaufort Park, South Farnborough and Leuchars, and six more are to be installed at Pershore, Filton, Ross-on-Wye, Anvil Green, Bingley Moor and Holme Moss by the autumn of 1974.

MOWOS Mk 2 is an interrogable system which uses the public switched telephone system. It provides mean wind speed and direction, atmospheric pressure, dry-bulb, wet-bulb and dew-point temperatures, duration of bright sunshine, rate of rainfall and cumulative rainfall. Spare channels are available for other data. The data are updated every five minutes.

The system has attracted the attention of several overseas governments and was exhibited at the meeting of the World Meteorological Organization Commission for Basic Systems held in Belgrade from 18 March to 5 April 1974.

THE MEASUREMENT OF RAINFALL BY RADAR

On 13 December 1973 a colloquium on the Quantitative Measurement of Areal Rainfall by Radar was held at the Meteorological Office College, Shinfield Park. It was organized jointly by the Water Resources Board and the Meteorological Office and was attended by about 60 invited delegates, mostly from the water industry. Results from the Dee Weather Radar Project were discussed and a report entitled 'The Use of a Radar Network for the Measurement and Quantitative Forecasting of Precipitation' was distributed. This report, which was written by staff of the Water Resources Board, the Meteorological Office, Plessey Radar Limited and the Greater London Council, assesses the potential benefits and costing of a network of weather radars in the United Kingdom. The possible locations of these radars and potential users of the resultant data are also discussed.

One of the problems in the accurate measurement of surface rainfall by radar occurs when the radar beam intercepts the melting layer. In order to minimize this effect, the beam width of the radar used in the Dee Weather Radar Project has recently been reduced from 2° to 1° . This has been achieved by changing the operating wavelength from S-band (10 cm) to C-band (5.6 cm).

NUMERICAL MODELS FOR LONGER-RANGE FORECASTING AND CLIMATE SIMULATION

The development of mathematical models for longer-range forecasting and simulation of climate continued at a high level. A complete version of the 11-layer model is now available, and the first of a series of 14-day prediction experiments planned for this year has been started. Results previously obtained from a 6-day mean of the model, which at that stage, however, did not include physical representation of the effects of radiation, were encouraging. Much work has also been done on the tropical model for use with the data due to be available from the GARP Tropical Experiment in the summer of 1974.

RADIOSONDE ASCENTS FROM MERCHANT SHIPS

The last voyage, in a six-year programme of radiosonde ascents made from merchant ships as a contribution to the World Weather Watch scheme, was completed in December 1973. The help willingly given to the meteorologist who sailed in each vessel by officers and crew members of the Sugar Line Company contributed significantly to the good results obtained. Communication delays in remote tropical regions and the lack of upper-wind observations prevented full benefit being gained from the efforts of those concerned. However, the programme provided 1437 soundings to a mean altitude of 21 km in regions not otherwise subject to radiosonde surveillance, thereby giving much useful information — especially for climatological purposes.

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NOTICES

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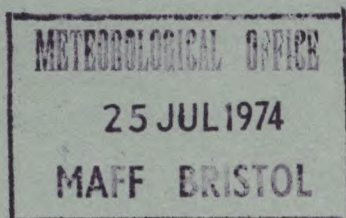
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RETIREMENT OF MR E. KNIGHTING

With the retirement on 23 April 1974 of Mr E. Knighting, the Meteorological Office lost a leading scientist who had played a large part in the development of both upper-air analysis and numerical weather forecasting since their early days.

When he left the teaching profession in January 1940 to join the Meteorological Office Mr Knighting soon found himself at the Central Forecasting Office, which was settling into its new quarters at Dunstable after being moved from London at the outbreak of war. Later he became a member of the eminent team under the direction of Dr Sverre Petterssen which established the techniques of upper-air analysis and wind forecasting for the wartime Royal Air Force. For the first time upper-air charts were drawn on a regular basis.

Leaving Dunstable in 1949, Mr Knighting undertook research at Headquarters for two years until, on promotion to Principal Scientific Officer, he was posted to Shoeburyness for duty with the Army units there.

Mr Knighting's association with numerical weather prediction began in 1955, when he was sent to Washington to study the methods being developed in the U.S.A. At this time numerical weather prediction had been the subject of active study both in the U.S.A. and in the Meteorological Office for a few years, and the United States Weather Bureau had decided to install its first computer in order to put numerical forecasting into operational practice. Returning to Dunstable after 10 months in Washington, Mr Knighting joined the small group which had been developing dynamical methods of forecasting there. He was promoted to Senior Principal Scientific Officer in 1959 and assumed leadership of the research group engaged in studies related to short-period forecasting. Later, in 1965, Mr Knighting was promoted to Deputy Chief Scientific Officer to fill the post of Deputy Director (Dynamical Research) with wider responsibilities for research in both synoptic and dynamical meteorology. The Meteorological Office College also came under his direction, and received the benefit of his wide knowledge and of his interest in teaching and the training of staff.

A mathematician by early training, Mr Knighting has made many personal contributions to meteorological research. These include studies of the structure of the atmospheric boundary layer in relation to radio propagation as well as

his later researches in the larger-scale aspects of dynamical meteorology. The Meteorological Office will miss Mr Knighting's clear judgement and firm guidance in its research activities.

Mr Knighting's many colleagues and friends in the Meteorological Office and in the many research institutes at home and abroad will, I know, wish him a long and happy future.

J. S. SAWYER

551.507.2

THE METEOROLOGICAL OFFSHORE BUOY OBSERVING EQUIPMENT EXPERIMENT, 1972

By K. J. T. SANDS

Summary. An experiment in which a small offshore buoy equipped with meteorological sensors was used is described. The buoy was on station in Cardigan Bay for three months in the summer of 1972. The results of the experiment are discussed and future plans are outlined.

Introduction. The Meteorological Office and the Directorate of Meteorology and Oceanographic Services (Navy) agreed in 1967 to collaborate in the development of ocean-data buoys. The Meteorological Office was to be responsible for meteorological sensors, data-handling equipment, transmission and recording equipment, and the Royal Navy for oceanographic sensors, buoy platforms, deployment and moorings. This article is partly based on a paper presented at a World Meteorological Organization Technical Conference in Tokyo in 1972.¹

History. The joint programme began in 1968 when a requirement arose for a small instrumented buoy to be used for air-sea interaction studies in the North Atlantic. The Royal Navy was able to provide a toroidal buoy of diameter 2.5 metres which could be deployed from the deck of a hydrographic research vessel. The toroid is made of a glass-reinforced plastic skin with an expanded polystyrene filling, and the superstructure is constructed from stainless-steel tube.

The initial instrumentation of the buoy was carried out by Messrs Plessey, who provided the recording equipment and interfaced it with sensors specified by the Meteorological Office. The data-handling equipment was an adaptation of an automatic climatological station in which data were stored by a magnetic-tape recorder. The equipment was housed in a watertight container and powered by lead-acid batteries in a separate compartment.

The meteorological sensors were basically those normally used at land stations, but had been modified for the rather specialized application. The experiment was regarded as an excellent opportunity to gain experience in the use of sensors in a marine environment, and measurements were made of pressure, air temperature, air-sea temperature difference, wet-bulb depression and wind speed. These elements were recorded every 15 minutes on $\frac{1}{4}$ -inch magnetic tape.

The sensors were mounted on a horizontal ring about 2 metres above the sea surface. Because toroidal buoys are 'wave-riders' the instruments remain clear of the water even in fairly rough weather. There is a tendency for the buoy to roll, but this can be reduced to some extent by the use of ballast.

The buoy was first tried out during an international air-sea interaction experiment (Operation ATEX) in the North Atlantic tradewind belt in February 1969. It was next used in Operation JASIN (Joint Air Sea Interaction), which took place near ocean weather station Juliett in June 1970. A second buoy of the same type was used to study the performance of pressure transducers in the marine environment. This experiment showed that it was possible to measure pressure to an accuracy of within about ± 0.5 mb.

Because these buoys had performed satisfactorily at sea, and because the second buoy offered the necessary data-handling facilities with ample spare channels, it was decided to use this 'test-bed' platform for evaluating marine sensors. If reasonably economic buoys are to be developed for operational service, they are likely to have severe power restrictions, and the system as a whole must provide satisfactory service over long periods without attention. In both respects it is the sensors which give most cause for concern.

The test-bed buoy, now known as the Offshore Buoy Observing Equipment (OBOE IA), marks the first step in a long-term programme of development and evaluation.

The buoy equipment. The original data-handling equipment was retained but several modifications were carried out. In order to provide real-time monitoring of the output of the meteorological sensors, a radio-telemetry link to a shore-station receiver was provided, whilst retaining the recording facility on the buoy as a safeguard against communication difficulties. The recording equipment is capable of handling eight analogue channels, which are switched sequentially to an encoder based on the successive-approximation principle. The signals are converted into 10-bit binary-data words (giving a resolution of 0.1 per cent), recorded serially on to $\frac{1}{4}$ -inch magnetic tape, and at the same time fed to the modulation stage of the radio transmitter. The 10-bit words are transmitted by using a two-tone frequency-shift system, the output power of the transmitter being 2 watts at a frequency of 151.5 MHz. An omnidirectional half-wave aerial, mounted 3.5 metres above the sea surface, is used on the buoy. Lead-acid batteries provide the power supplies, and their capacity is such that the buoy equipment will run for six weeks from a single charge. The internal clock now switches on the data-recording equipment and radio transmitter at half-hourly intervals, a complete transmission cycle taking about 75 seconds. During the 'off' periods, power is supplied only to the clock system. Each sensing transducer provides a voltage in the range 0–5 volts d.c. The block diagram (Figure 1) shows the essential features of the buoy system.

Functions of the channels

Channel 1 provides data on the state of the batteries for four successive transmissions, while the next four transmissions give a reference signal, which makes it possible for the data-handling system as a whole to be calibrated. This sequence is repeated throughout the 24 hours.

Channels 2, 3 and 4. These channels are used for the measurement of temperature. On channel 2, differentially connected electrical resistance thermometers (ERT) are used to measure the air-sea temperature difference in the range $\pm 10^\circ\text{C}$ by means of a Kelvin bridge and an operational amplifier. Linearity is better than 0.1 per cent. On channel 3, an ERT with Kelvin bridge and interface amplifier is used to measure air temperature in the range -10°

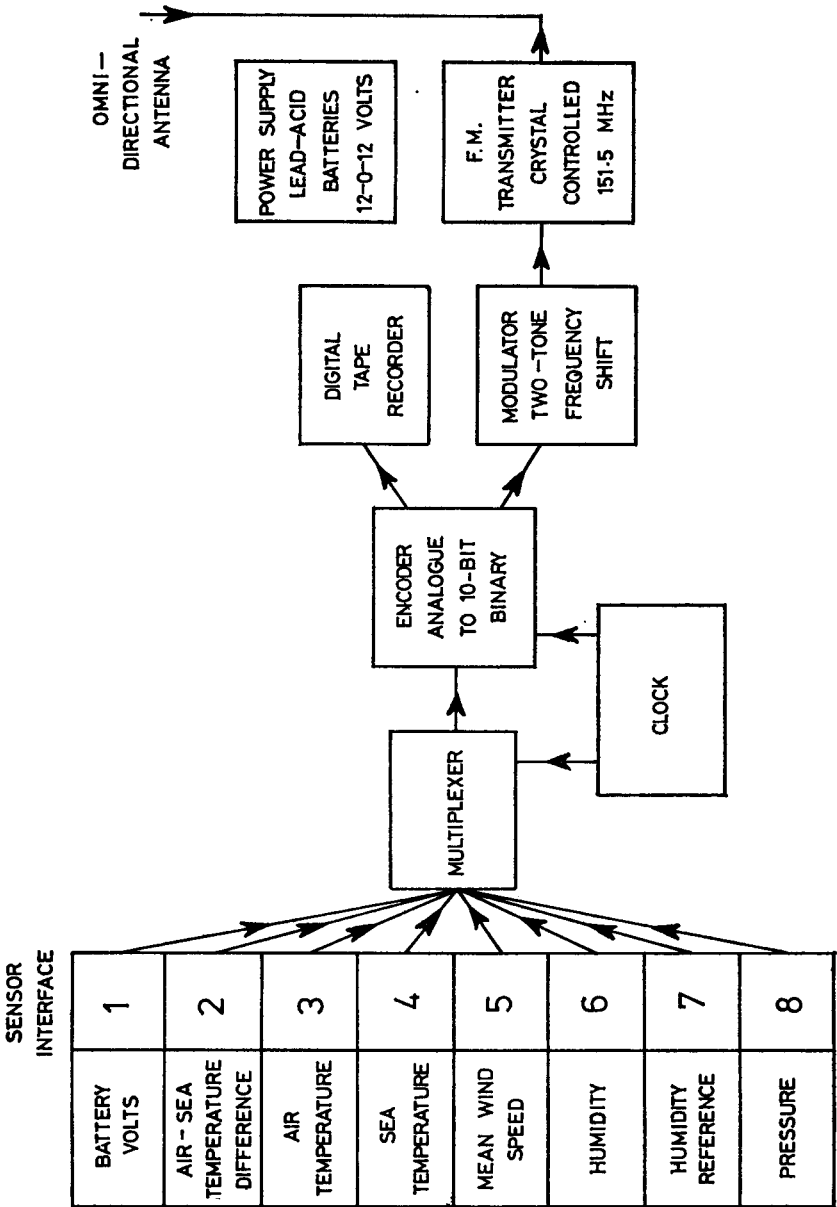


FIGURE 1—BLOCK DIAGRAM OF BUOY EQUIPMENT

to $+25^{\circ}\text{C}$. On channel 4, a measure of redundancy is provided by the measurement of sea temperature in the range 0° to $+20^{\circ}\text{C}$. The sea sensors, mounted at a depth of 1 metre, are sheathed in neoprene, and have a time constant of 20 minutes. The air thermometers are exposed in an unventilated marine screen.

Channel 5. A conventional cup anemometer with a.c. generator is used to measure wind speed in the range 3–100 kt via a frequency-to-voltage converter and a 1-minute averaging circuit, linearity being better than 1 per cent. The cup arms are specially strengthened, and the body is modified to prevent the ingress of sea water or spray by the inclusion of a moisture trap. The averaging period is restricted to one minute partly by the power restriction, and partly by the design of the existing timer unit. There would be no difficulty in providing an alternative averaging time if required at a later stage. Wind-tunnel tests have shown that the anemometer calibration does not follow a cosine law when the sensor tilts, rolling movement up to 40° having no significant effect.

Channels 6 and 7. Relative humidity in the range 20–100 per cent is measured with a PCRC-11 element (Phys-Chemical Research Corporation) and a 22-Hz a.c. bridge feeding an a.c.-to-d.c. converter, the output being transmitted on channel 6. On channel 7, the resistance of a second PCRC-11 element, exposed to an atmosphere of known humidity above a saturated salt solution, is measured by the same bridge and associated electronic circuits. Both elements are housed in a second marine screen. Folland² finds the PCRC-11 elements to be reasonably stable and apparently washable. Equilibrium is reached within 5 seconds of switching on, and the average power consumption can consequently be reduced to about 10 milliwatts. The sensors are protected by cellulose acetate sheet, 0.025 mm in thickness, from contamination by spray. The elements are individually calibrated in a two-pressure precision humidity generator developed by the Meteorological Office, both before and after use at sea.

Channel 8. A temperature-compensated aneroid barometer with electrical output is used to measure atmospheric pressure in the range 950–1050 mb. The pressure transducer which is a standard commercial product is located in the lower compartment of the data-logger box and vented to the atmosphere through a directional static pressure head. This type of transducer had shown an accuracy of about ± 0.25 mb, relative to a working standard, over a period of several months at a land station.

The shore station (Figure 2). Because of the early decision to use the original data-handling equipment on the buoy with the minimum modification, the data format thus determined greatly influenced the design of the shore-station equipment. In the interests of economy, it was decided to use a standard Meteorological Office radio receiver, but, because of the shortcomings in the stability of the receiver at high frequencies, a commercial frequency-converter was introduced to change the incoming signal to a lower and more stable frequency. The signal is received on a six-element YAGI aerial. After FM detection by the receiver, the signal is processed by the Marine Buoy Decoder (see Plate III). The signal decoder has facilities for checking the incoming signal for transmission errors and for holding the complete message in store until the time of the next transmission. The contents of the message store are displayed one word (channel) at a time in the form of decimal numbers in the range 0 to 1023, the word displayed being identified by a channel number 1 to 8. The message can be read, word by word, by means of a stepping switch.

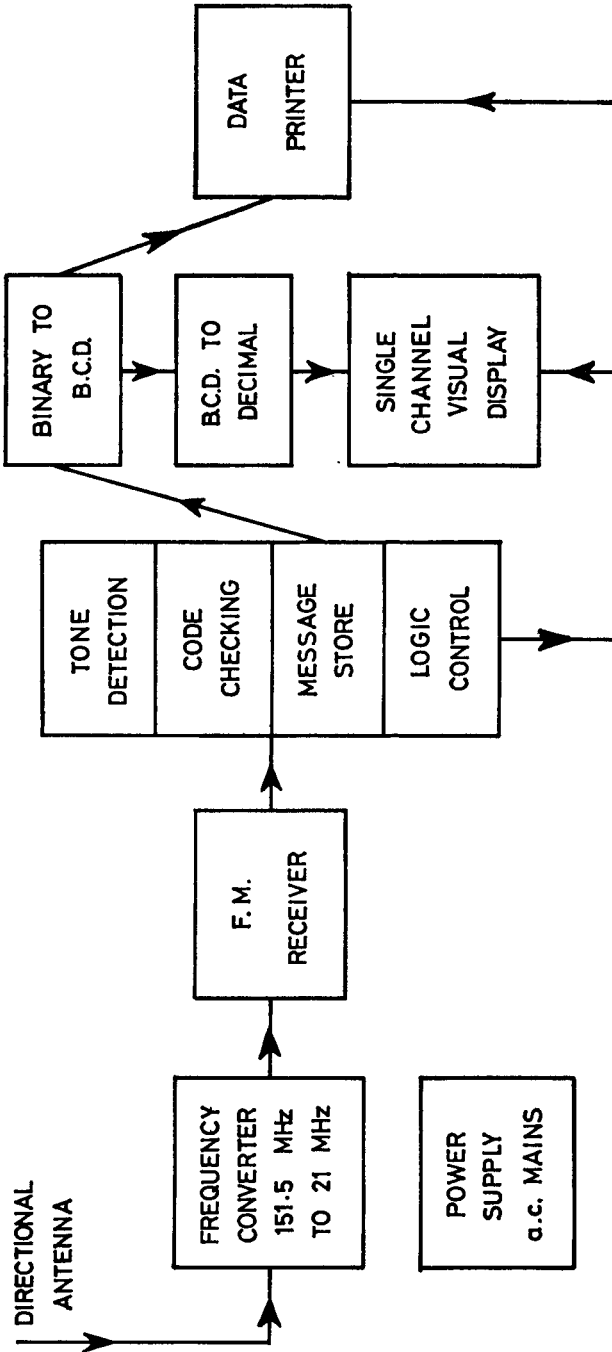


FIGURE 2—BLOCK DIAGRAM OF SHORE-STATION EQUIPMENT
B.C.D. = Binary-coded decimal.

The reading process is non-destructive and can be repeated. After message checking is completed, the data are automatically printed out on a five-column paper roll. The next transmission clears the store of the previous message, the incoming signal restarting the decoding cycle. Once the receiver has been tuned (after a warming-up period) to the buoy frequency, the operation of the shore station is completely automatic. Solid-state electronic components are used throughout the decoder and this gives a very high degree of reliability.

Operation. At the time when the development of the first air-sea inter-action buoy began in 1968, a second requirement arose for real-time measurements over the sea near the Royal Aircraft Establishment at Aberporth. For its first sea trials, therefore, it was decided to deploy the buoy in the Irish Sea, some 10 km off the coast at Aberporth. The position chosen is partially sheltered from the prevailing south-westerly winds by a small headland. Calibration and testing of the complete system took place in April 1972 at Beaufort Park, and the equipment was moved by road to Aberporth early in May. The shore station equipment was installed in the Meteorological Office, situated on top of a cliff approximately 130 metres above sea level. Checks for mutual interference by the buoy telemetry equipment and equipment used by the Royal Aircraft Establishment were satisfactory. A further check of the buoy system took place before the buoy was taken to Pembroke Dock in the middle of May. The Royal Naval Dockyard at Pembroke Dock had undertaken the task of placing the buoy on station in Cardigan Bay. After two weeks' delay caused by a combination of bad weather and mechanical mishaps, the buoy was placed on station (see Plate IV) at a point where the mean sea depth is 12 fathoms (approximately 22 metres).

A final check of the sensors and the erection of the transmitting aerial were carried out when the buoy was on station, the first transmission of data taking place at 18 GMT on 1 June. The first few days of operation showed a large percentage of corrupt messages. Measurements made at the shore station revealed that a shift had taken place in the modulation frequency of the radio transmitter. The shore-based decoding equipment was adjusted to allow for the shift and an immediate improvement in data-acquisition occurred. Half-hourly transmissions of data continued throughout June, July and most of August with a recovery rate of more than 90 per cent. All sensors performed well except the pressure transducer, which was later found to have developed an electrical fault. Late in August transmissions from the buoy became intermittent and the buoy was lifted from station on 1 September and returned to Pembroke Dock. The buoy was examined briefly at the dockside and very little damage was noted. The 'electronics' compartment had remained completely sealed and there was no obvious damage to the superstructure or sensors.

Results. The magnetic tape removed from the data-recording equipment at the end of the trial was translated by Messrs Plessey and provided a useful check on the real-time transmitted data. A detailed analysis of these data, together with comparisons with control readings, will be the subject of a later paper. However, initial examination of the data shows that there was good self-consistency in the temperature measurements on channels 2, 3 and 4. Temperature measurements made on land in westerly situations and the occasional sea temperature gave confidence in the data being transmitted. Wind-speed data were compared with readings taken from a floating platform moored 2 km

from the position of OBOE IA and also with selected readings taken at the shore station. After taking into account the difference in exposure appropriate to the three sets of measurements there is fairly close agreement between them. The humidity elements show promise as operational sensors for long-term unattended use on ocean buoys, though there was a drift in calibration of about 5 per cent in relative humidity over the first two months by both sensors.

Conclusions and future developments. This first sea trial with the off-shore telemetering buoy has proved its value as a test bed for the exposure and evaluation of marine sensors. It is essential to complete the development and evaluation of a complete suite of reliable marine sensors well in advance of the introduction of networks of operational buoys, automatic light-towers and other suitable platforms. It had been hoped that frequent control readings would be obtained from the trials vessel used by the Royal Aircraft Establishment, but the operation of the vessel in its primary role prevented this from being realized. For any future trials a means must be found of obtaining adequate control readings, for only in this way can the accuracy of the sensors be assessed under all relevant environmental conditions.

After checking and recalibration of sensors and associated electronic circuits, the buoy was redeployed in the Thames Estuary during the period February–April 1973, the shore station being at Shoeburyness. Daily control readings were obtained from the end of Southend Pier (approximately 1.5 km from the buoy), and from the Meteorological Office at Shoeburyness. After some early troubles caused by the ingress of water into the ‘electronics’ compartment, the buoy again operated satisfactorily, over 95 per cent of the data being recovered. Data from the buoy were passed via Shoeburyness to the London Weather Centre several times each day, and were useful in enabling the Weather Centre to provide up-to-date information to the Port of London Authority in connection with the passage of large vessels up river to the docks. This second trial suggested that OBOE IA could fill an operational role in more or less its present configuration.

In order to make further progress with the general programme of development, a rather larger buoy was needed. The Royal Navy had obtained a 3.5-m diameter steel buoy for use in the joint programme and it is intended to use it as a second test-bed platform for the evaluation of improved power supplies, sensors, data-handling and communication links. This buoy will be known as OBOE II. The number of data channels planned will allow transmission of data on the general state of the equipment, buoy motion, internal temperature of ‘electronics’, etc., as well as oceanographic measurements. It is hoped that the buoy will operate unattended for 6-month periods. OBOE II should be operating towards the end of 1974.

Acknowledgements. The contribution of Mr D. Painting, who designed and built the shore-station decoder, and the help and advice given by the Hydrographic Department of the Royal Navy are gratefully acknowledged.

REFERENCES

1. BLACKWELL, M. J. and SANDS, K. J. T.; Offshore telemetering buoy for real-time monitoring of sensor performance. Geneva, World Meteorological Organization. Reports on Marine Science Affairs, No. 7, Geneva, 1973, pp. 199–201.
2. FOLLAND, C. K.; Low-power humidity sensor for unattended use on buoys. Geneva, World Meteorological Organization. Reports on Marine Science Affairs, No. 7, Geneva, 1973, pp. 186–198.

NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1973

By D. H. McINTOSH and MARY HALLISSEY
(Department of Meteorology, University of Edinburgh)

Positive observations of noctilucent clouds (NLC) between 25 May and 8 August 1973, made by the network of observers associated with the Data Centre at Edinburgh, appear in Table I. These dates cover the period of optimum viewing of the clouds between geographic latitudes 50° and 60°N. The period of time during which the clouds were observed appears in the second column, and should not necessarily be taken as the extent of the display; this is stated where possible, but it is obviously difficult, particularly for voluntary observers, to record a display to the point of disappearance. Observations of the characteristics of the observed NLC are entered in the third column. The remaining columns contain observations from selected stations, the latitude and longitude of which are given to the nearest half degree. The maximum elevation and limiting azimuths of the observed cloud field at the stated times appear in the last two columns.

In Table II are listed observations of the clouds on 29–30 June 1971, made at Bunnik in the Netherlands, and in Scotland. In the previously published list¹ 'No NLC' was entered for 29 June 1971. Two 'query' reports had in fact been received for that night. It has, however, always been the practice to withhold from publication any observations considered doubtful, so that although entered in our own records, they were not in the published list. Dr Zwaart's notes and a series of colour photographs now leave no doubt about the presence of the clouds over Denmark, and the queried reports are also published.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1973

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths degrees
26–27 May	0210–0240	Bands and wisps drifting towards east and receding slightly. Suspected visible also from southern Scotland 2130–2330 UT.	55°N 4.5°W 52°N 0°	0222	20	010–040
3–4 June	2150	Bands and billows against veil background seen from southern England and suspected visible from north-east Scotland.	57°N 3.5°W 51°N 1°E	0050 2150	10	330–020
6–7	0120–0225	Bright display of bands and veil, widespread and beyond observer's zenith at 0200 UT. Display still present at 0225 UT.	52°N 0°	0200	90	
7–8	0050–0220	Faint, diffuse bands and wisps, not so bright as previous night, but 'delicate and beautiful'.	55°N 4.5°W 53°N 0.5°E 52°N 0°	0050 0150 0145	5 14 10	035 340–035 340–020
15–16	2200	Bands seen low in north.	55.5°N 4.5°W			
16–17	2200–2215	Bright veil in northern sky, but no obvious structure.	55.5°N 12.5°E			
17–18	2245–2305	NLC seen from Denmark, brightest in NNE, decreasing brightness with height.	55°N 14.5°E	2245 2305	7 12	020–045
18–19	2220–2325	NLC visible from Denmark. Slowly changing structure from veil and bands, with violent increase of brightness at 2255 UT and billow formation. Greatest brightness 2325 UT when new NLC noted in NE. Western movement of clouds. Observations ended 2325 UT.	55°N 14.5°E	2220 2315 2325	12 15 20	315–045
23–24	2200–2340	Unspectacular low-powered display of NLC. Seen Scotland and Denmark.	55.5°N 4.5°W 55°N 14.5°E	2200 2210 2255	10 12 8	340–045

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths degrees
24–25	2120–2310	NLC again visible from Denmark. Weak bands at first visible only through binoculars, increased in brightness, elevation and extent. Observations ended at 2310 UT.	55°N 14·5°E	2140 2210 2310	10 12 8	045 340–045
25–26	2155	Veil and bands of medium brightness seen from southern England, almost to zenith. Cloudy over rest of Britain.	51°N 1°E	2155	52	360–030
27–28 June	2340–0005	Two bands of NLC clearly identified though faint in bright sky. Disappeared into rising dawn.	55·5°N 4·5°W	2340 2400	13 13	340–005 002–015
28–29	2245–0045	Band of NLC visible from northern England.	55°N 1·5°W	2245 0045	7 9	340–020 360–030
30 June– 1 July	2145–2215	From Denmark low-brightness bands of NLC visible above haze to 15°, with small areas of short-lived NLC at higher elevation.	55·5°N 12·5°E			
2–3 July	2150–0200	NLC, brilliant at times, observed from central and south-west Scotland and northern England. Herring-bone formation, billows and S-shaped bands suggested multiple-layered cloud. Display observed from Denmark with less brilliance.	56·5°N 3°W	2310	21	300–030
				2340	25	300–020
			56°N 4·5°W	2300	18	350–040
				2400	19	320–050
				0010	20	300–045
				0030	14	300–050
				0100	15	340–070
			55·5°N 4·5°W	2239	14	028–040
				2300	20	350–050
				0034	12	
			55°N 4·5°W			
			55°N 1·5°W	2245	12	350–010
3–4	2145–0050	Weak but widespread NLC seen from Denmark at 2145 UT with band and veil structure, becoming much brighter at 2245 UT. In western Scotland tenuous bands and brighter billows visible until tropospheric cloud obscured forms. Very bright display of veil, bands and billows. For all observers northern border hidden by cloud banks.	56·5°N 7°W	2255	15	330–030
				0045	12	340–020
			55°N 14·5°E	2140	10	300
				2215	12	315–045
				2320	18	315–065
			56·5°N 3°W	2350	10	340–045
			55°N 14·5°E	0050	10	030
				2145	25	300–045
4–5	2130–0130		57·5°N 3·5°W	2345	19	330–040
				0015	13	
			56·5°N 3°W	2345	9	010–030
				0015	9	350–040
			56°N 10°E	2130	20	315
			55·5°N 4·5°W			
			54°N 4·5°W	2245	10	315–360
				2345	5	360–020
			53·5°N 3°W	2210	11	330–030
			52°N 8·5°W	2245	9	337–017
			56°N 10°E	2145	40	290–045
				2345	15	045
8–9	2145–0045	NLC observed from Denmark. Colour photographs show billows at high altitude. New bright veil and bands appeared later at 2325 UT in NE. Formation almost unchanged when observations ended at 0045 UT.				
9–10	2150–2215	Short-duration NLC seen from Denmark, at first with binoculars. Weak bands in NE. Observations hampered by tropospheric cloud.	56°N 10°E			
13–14	2210–0015	Weak display seen from Denmark, maximum brightness 2340 UT. New formations visible low NE as sky became too light to observe.	56°N 10°E	2210 2340	10 12	045
15–16	2245–2305	Weak display seen from Copenhagen.	55·5°N 12·5°E			
19–20	0200	NLC seen through gap in tropospheric clouds.	53°N 0·5°E	0200	6	020
23–24	2300–0100	Very bright NLC visible NW—from northern Scotland and later, 2350 UT, to NNW from western Scotland. Onset of tropospheric cloud prevented later observations.	58·5°N 3°W 57·5°N 7·5°W	2300 2350	15 9	315–020 340–360
24–25	2350–0200	NLC seen from western Scotland; no details.	57·5°N 7·5°W			
26–27	0040, 0230	Narrow band of NLC seen from south-western Scotland 0040 UT and again faintly at 0230 UT.	55°N 4·5°W			

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths degrees
28–29	2015–2230 0410, 0422	Reported from Copenhagen as brightest NLC of the season; veil and bands low to north. Bright bands and billows seen very low to north from aircraft over west Atlantic, earlier reporting auroral display.	55·5°N 12·5°E 52·5°N 35°W	0410 0422	3 4	300–050 360–045
6–7 Aug.	0050–0315	Veil with whirls seen from western and central Scotland as tropospheric cloud cleared. Earlier seen as narrow band from western and south-western Scotland.	56·5°N 7°W 56·5°N 3°W 55°N 4·5°W	0225	13	350–060
7–8	2300 0230–0325	Short-lived display. Medium brightness billows seen from north-eastern Scotland, and faintly from central and south-western Scotland.	57°N 2°W 55·5°N 4·5°W 55°N 4·5°W	0230 0315	35 36	350–040 360–080

TABLE II—ADDITIONAL DISPLAYS OF NOCTILUCENT CLOUD OVER WESTERN EUROPE DURING 1971

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths degrees
29–30 June	2045–2145 2330 0030–0150	From Denmark veil, bands, billows showing clearly against fairly bright sky. From Scotland marked red coloration at lower edge nearest horizon. All observations terminated owing to onset of tropospheric cloud.	56°N 4·5°W 55°N 4·5°W 52°N 5°E	0145 2100	15 10	020–040 315–340

It is felt that wider recognition of the clouds by a very reliable network of observers should now ensure that a high percentage of displays visible in this region is recorded whenever meteorological conditions permit. It is possible, however, that instances of the less obvious presence of noctilucent clouds may pass unnoticed, largely owing to factors hampering observations other than the obvious one of ordinary cloudiness, such as moonlight, lack of eye adaptation or presence of atmospheric dust. Reliable comparison of annual frequency is therefore as yet difficult to make, and it would seem that sheer weight of observational data, both positive and negative, is necessary to enable a reliable estimate of noctilucent-cloud occurrence to be made.

During 1973 the clouds were visible on 26–27 May and 7–8 August, which are near the limits of the optimum viewing period for western Europe. Observations for 11–12, 17–18 August and 8–9 September were received, but are regarded as doubtful, and are not included in the published list. They are, however, mentioned because although the clouds are thought to recede polewards in late summer, the possibility of their appearance in western Europe at other times cannot yet be ruled out.

Numerically, the peak of the observing period, which in 1971 and 1972 occurred in the first half of July, this year (1973) appeared in the latter half of June. Observers in Cambridge and in Denmark stressed the richness of the displays seen this season, but in the British Isles generally this was not the case. Cloudy conditions prevailed in most areas of the country, and from the events listed it is obvious that clear skies over Denmark were instrumental in ensuring that a high percentage of NLC occurrences over western Europe were in fact recorded.

Points of interest in relation to noctilucent clouds, contained in recent papers, are the reports of a 'bright layer' at about 80 km made by Russian cosmonauts,² and the suggestion that NLC occurrences be considered in relation to solar activity following the apparent detection, in further rocket experiments at Kiruna in 1970 and 1971, of the presence of heavy metal particles of solar origin in the clouds.³

The help of the many observers who have sent their reports, many accompanied by sketches, to the Data Collection Centre at the Balfour Stewart Laboratory, Department of Meteorology, University of Edinburgh, is gratefully acknowledged. Excellent photographs have also been submitted from Prestwick and Denmark of the displays seen on 18–19, 24–25 June, 2–3, 3–4, 8–9 and 13–14 July.

REFERENCES

1. PATON, J.; Noctilucent clouds over western Europe during 1971. *Met Mag*, London, 101, 1972, pp. 181–185.
2. FEOKTISTOV, K. P., ROZENBERG, G. V., SANDOMIRSKY, A. B., SERGEYEVICH, V. N. and SONECHKIN, D. M.; Some of the results of the observations conducted during the flight of the spaceship "Voskhod". GARCIA, R. V. and MALONE, T. F. (editors); Problems of atmospheric circulation, a Session of the Sixth International Space Science Symposium, Mar del Plata, Argentina, May 11–19, 1965. London, Macmillan, 1966, pp. 176–186.
3. HEMENWAY, C. L., HALLGREN, D. S. and SCHMALBERGER, D. C.; Stardust. *Nature*, London, 238, 1972, pp. 256–260.

551.515.3

THE TORNADOES OF 26 JUNE 1973

By K. W. WHYTE

Summary. An analysis of the synoptic situation together with evidence from radar and rainfall records shows that the tornadoes at Cranfield on 26 June 1973 were associated with a severe travelling storm of the wind-shear type. The consideration of some previous occurrences of severe storms and tornadoes demonstrates certain similarities between those occasions and 26 June.

Introduction. On 26 June 1973 at about 13 GMT two tornadoes occurred at the Environmental Sciences Research Unit's laboratory at Cranfield, Bedfordshire. The second of these was strong enough to cause considerable structural damage. Later in the afternoon one or more tornadoes were also responsible for damage to buildings and trees at the villages of Parson Drove and Tydd St Giles near Wisbech in Cambridgeshire, but it seems likely that these were associated with a different storm from that which caused the tornadoes at Cranfield.

The purpose of this paper is not to attempt any comprehensive explanation of the tornadoes of 26 June, as it is recognized that without a dense network of observations a complete understanding of such mesoscale phenomena cannot be hoped for. Nevertheless an analysis of the situation in which the tornadoes occurred shows that this occasion was similar in many respects to several of those on which severe storms and tornadoes have been recorded in the past.

Description of the tornadoes. The electrical anemograph record from Cranfield is shown in Plate I. The first tornado occurred at about 1242 GMT and gave a measured maximum gust of $27\frac{1}{2}$ m/s (53 kt). This caused no damage. The second occurred at 1304 GMT and produced a measured maximum gust of

38 m/s (74 kt). The record ends at this point, as the electrical power was disconnected for safety reasons following the damage to the building. The anemometer was at a distance of about 100 metres from the line taken by the second tornado, so that the speed nearer the centre was probably much greater. The damaged building is shown in Plate II. The maximum gust and the damage which was caused indicate that the second Cranfield tornado was at least of strength F1 on the Fujita scale,¹ and the damage at Parson Drove suggests that the tornado there was probably also of strength F1. It is of interest that the maximum gust at Cranfield was almost the same as the 85-mile/h (74-kt) gust recorded by the Shoeburyness anemometer at the time of the tornado of 20 October 1949.² This gust was stated to have been measured on the edge of a 100-yd wide track.

The track taken by the second Cranfield tornado is shown in Figure 1. Tagg³ has briefly described the events at Cranfield and a more complete description of the damage caused is given in the Building Research Establishment's report.⁴

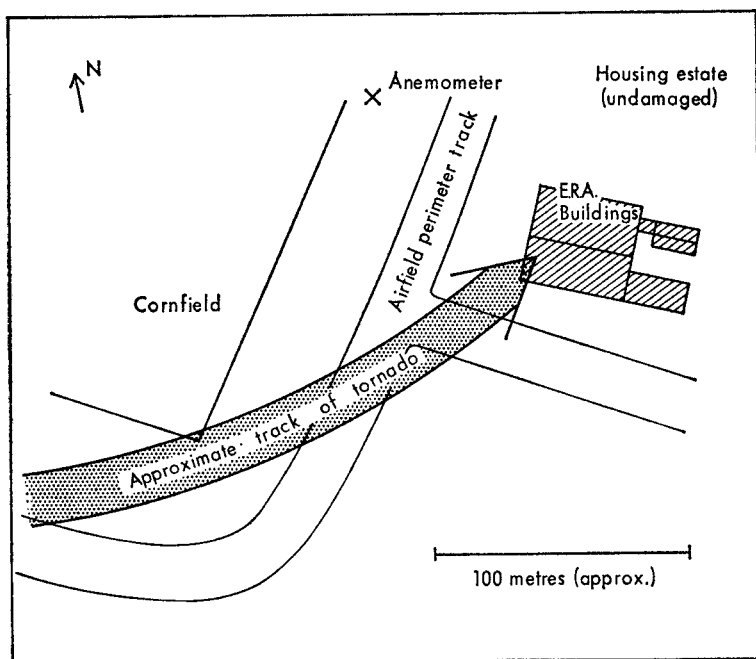


FIGURE 1—PLAN SHOWING THE TRACK OF THE SECOND CRANFIELD TORNADO

Synoptic situation. The surface chart for 12 GMT on 26 June 1973 is shown in Figure 2. A depression of surface pressure 1000 mb was centred over Iceland and its associated cold front, having cleared Scotland and Ireland the previous day, lay almost stationary from Durham to Pembrokeshire through a weak ridge of about 1020 mb which covered Scotland and Northern Ireland. There was a general easterly flow over southern England which was under the influence of a continental depression with its main centre over Spain.

The Icelandic vortex extended throughout the troposphere. Above the 850-mb level the flow over the British Isles, ahead of the upper trough to the

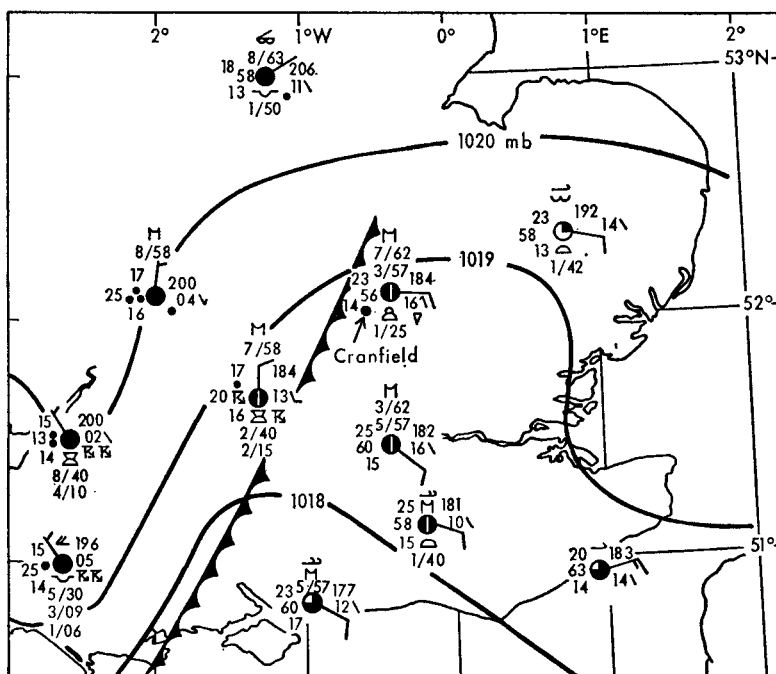


FIGURE 2—SURFACE ANALYSIS FOR 12 GMT ON 26 JUNE 1973

west of Ireland, was from the south-west, veering slightly and strengthening with height. Figure 3 shows the 500-mb contour and 1000–500-mb thickness fields at 12 GMT.

Ahead of the surface cold front there was a large area of rain including some moderate outbreaks over the north and west Midlands and Lincolnshire. Thunderstorms, which were first located over the English Channel in the early hours, broke out in the south-west during the morning, and travelling north-eastwards with the upper flow had reached Wiltshire and Oxfordshire by 10 GMT.

During the morning there was a line of low-level convergence stretching from near the Wash to Dorset. To the south-east light or moderate easterly winds were bringing warm air from the Continent and by 12 GMT temperatures were around 24°C. There were generally small amounts of cumulus below broken cirrostratus and altocumulus. By contrast, to the north-west but south of the Midlands rain-area, skies were overcast, temperatures about 18°C, and the wind was a light north or north-easterly. There was no significant difference across this line in the reported dew-points which were around 14° or 15°C, and the lower temperatures on the north-western side of the line were probably a result of cooling by precipitation combined with a lack of insolation. At 12 GMT a well-marked trough was present in the surface isobars, and the convergence line moved south-eastwards with it during the afternoon as a 'cold front' at a speed of about 5 kt. This anomalous motion against the pressure gradient was probably the result of the isallobaric gradient which was locally sufficiently strong to overcome the effect of the pressure

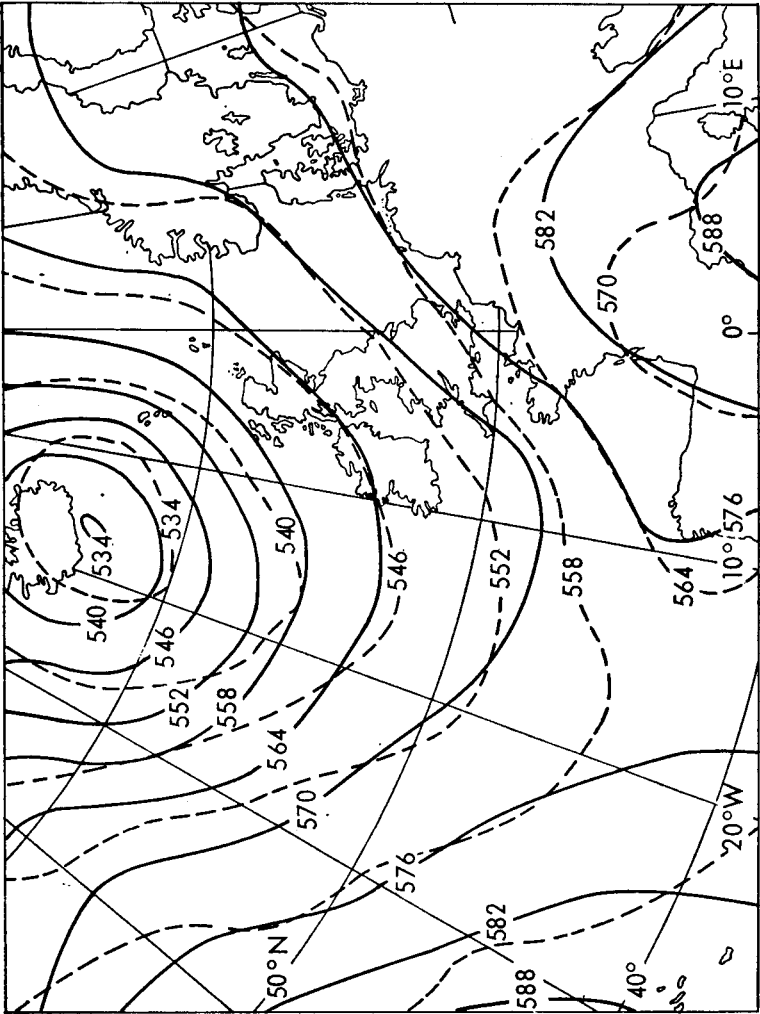


FIGURE 3—300-mb contours and 1000-500-mb thickness in decametres
AT 12 GMT ON 26 JUNE 1973
—— Contours - - - - Thickness

field. The front's progress, which is shown in Figure 4, could be followed by the times of the change in wind direction at the various stations, and it was passing through Cranfield at about the time of the main tornado.

It would seem that one or more of the medium-level storms which were advancing from the south-west developed into a severe storm cell organized on the lines proposed by Browning,^{5, 6} and that this cell was maintained by the vertical wind shear between the warm moist north-easterlies at the surface and the upper south-westerlies. In addition the convergence at the surface 'front' in conjunction with the Chiltern ridge may have provided the initial twisting stimulus necessary for the formation of the tornado.

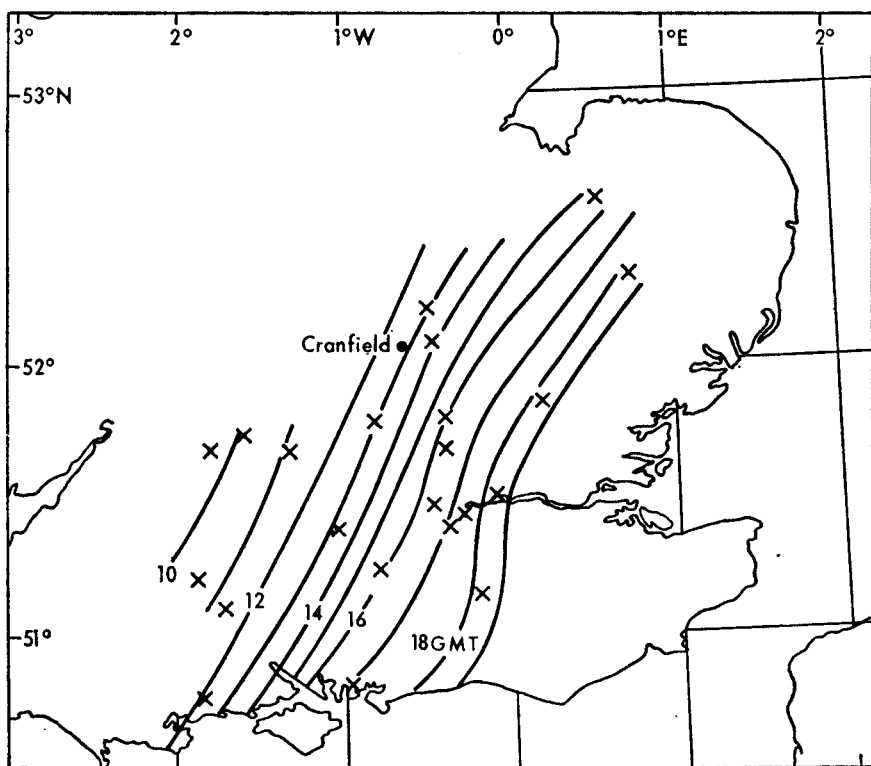
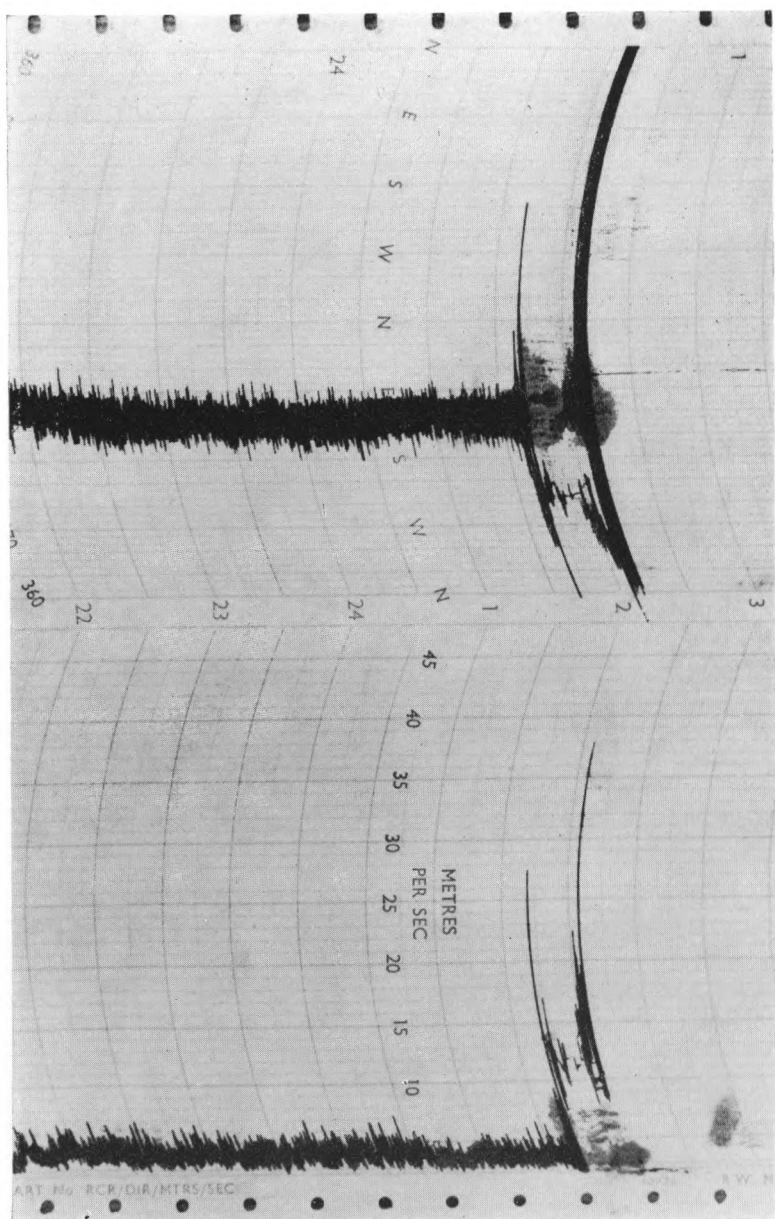


FIGURE 4—SUCCESSIVE HOURLY POSITIONS OF THE COLD FRONT DEPICTED IN FIGURE 2, AS DETERMINED BY ANEMOGRAMS AND WIND REPORTS FROM STATIONS MARKED WITH A CROSS

The Crawley and Hemsby midday ascents are shown in Figure 5. The Crawley ascent is moist, especially below 750 mb, and is unstable to the surface temperature, although only marginally if one takes the lowest 50-mb layer as defining a reasonable parcel. Hemsby's sounding is similar to Crawley's though drier in the lower layers, and the latent instability would be released if the surface temperature were to rise to about 25°C. (During the afternoon there were only a few isolated showers to the south-east of the Wash-Dorset front.) There is certainly no evidence of the stable layer with dry air above, which is considered to be one of the conditions for the formation of severe local storms



Photograph by courtesy of Mr J. R. Tagg, Environmental Sciences Research Unit, Cranfield.

PLATE I—CRANFIELD ANEMOGRAM FOR 26 JUNE 1973

The time scale is in British Summer Time and is incorrect by 12 hours (see page 160).



Photograph by courtesy of Dr K. J. Eaton, Building Research Establishment, Garston.

PLATE II—THE SOUTH-WEST CORNER OF THE DAMAGED ENVIRONMENTAL SCIENCES
RESEARCH UNIT BUILDING AFTER THE SECOND CRANFIELD TORNADO

See page 161.

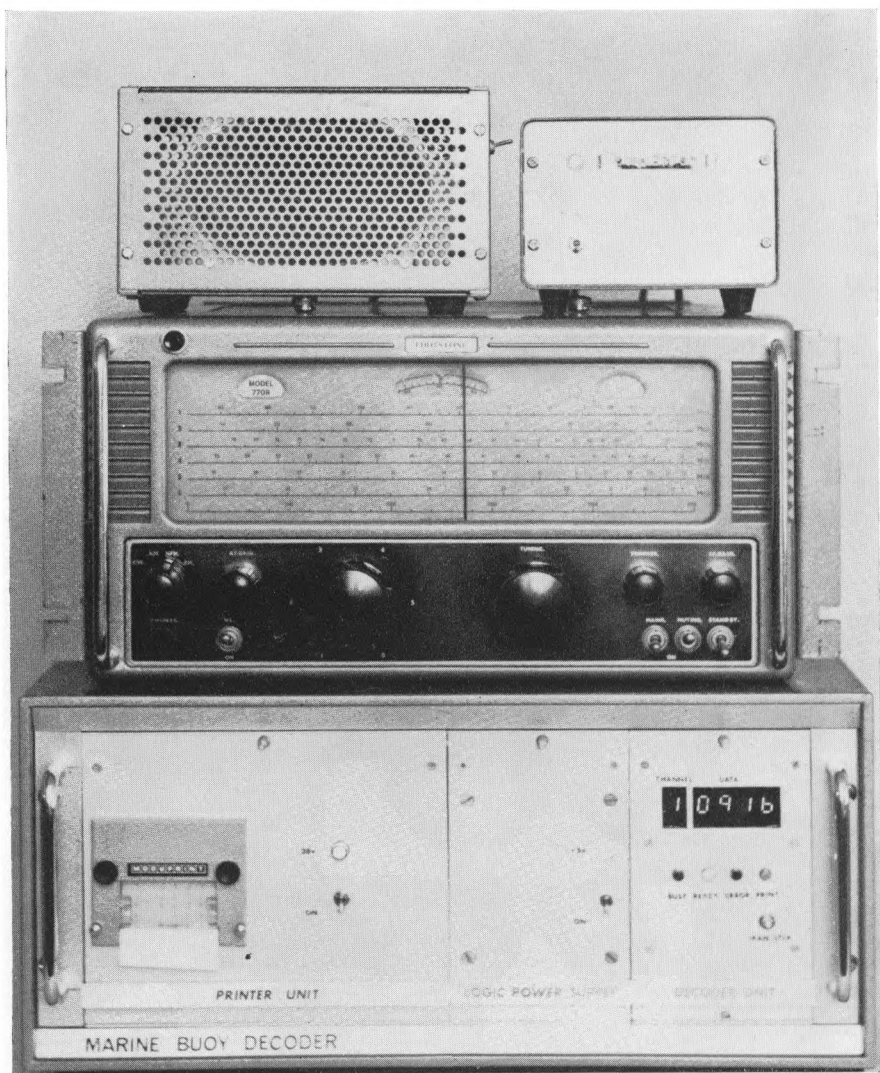


PLATE III—THE SHORE-BASED RECEIVING STATION

See page 153.

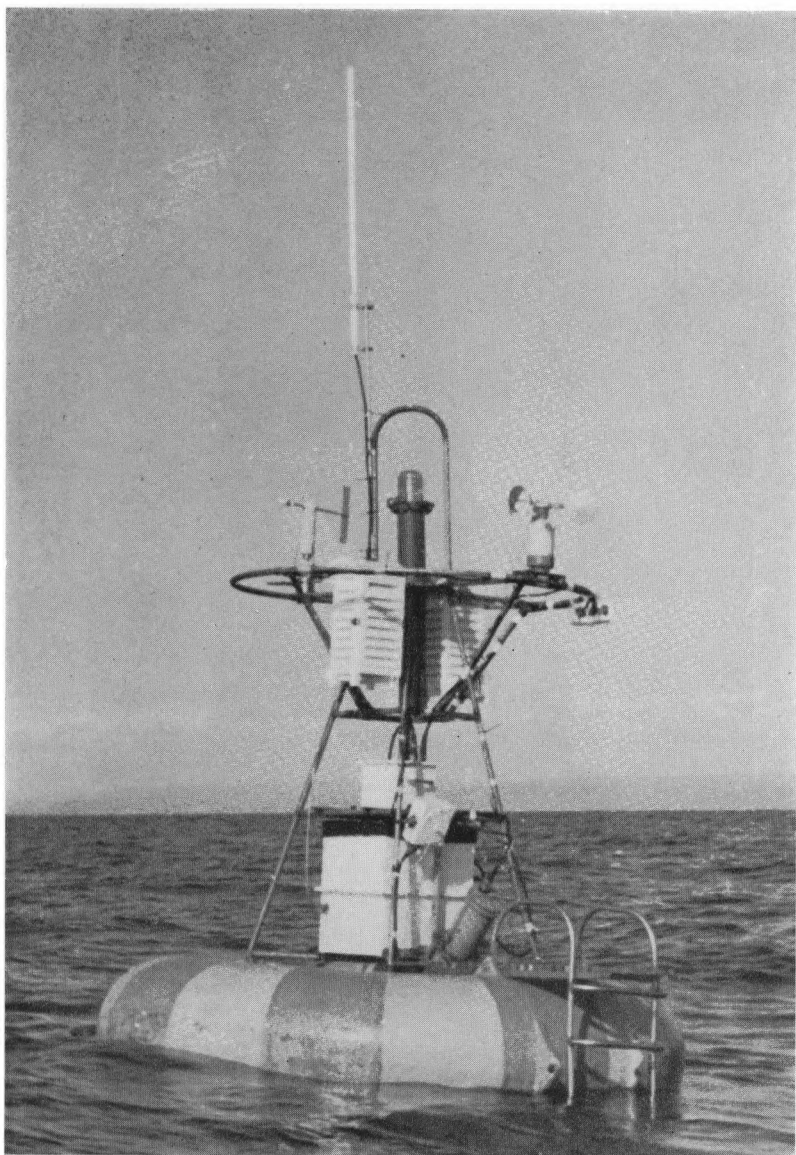


PLATE IV—OBOE 1A ON STATION OFF ABERPORTH
See page 155.

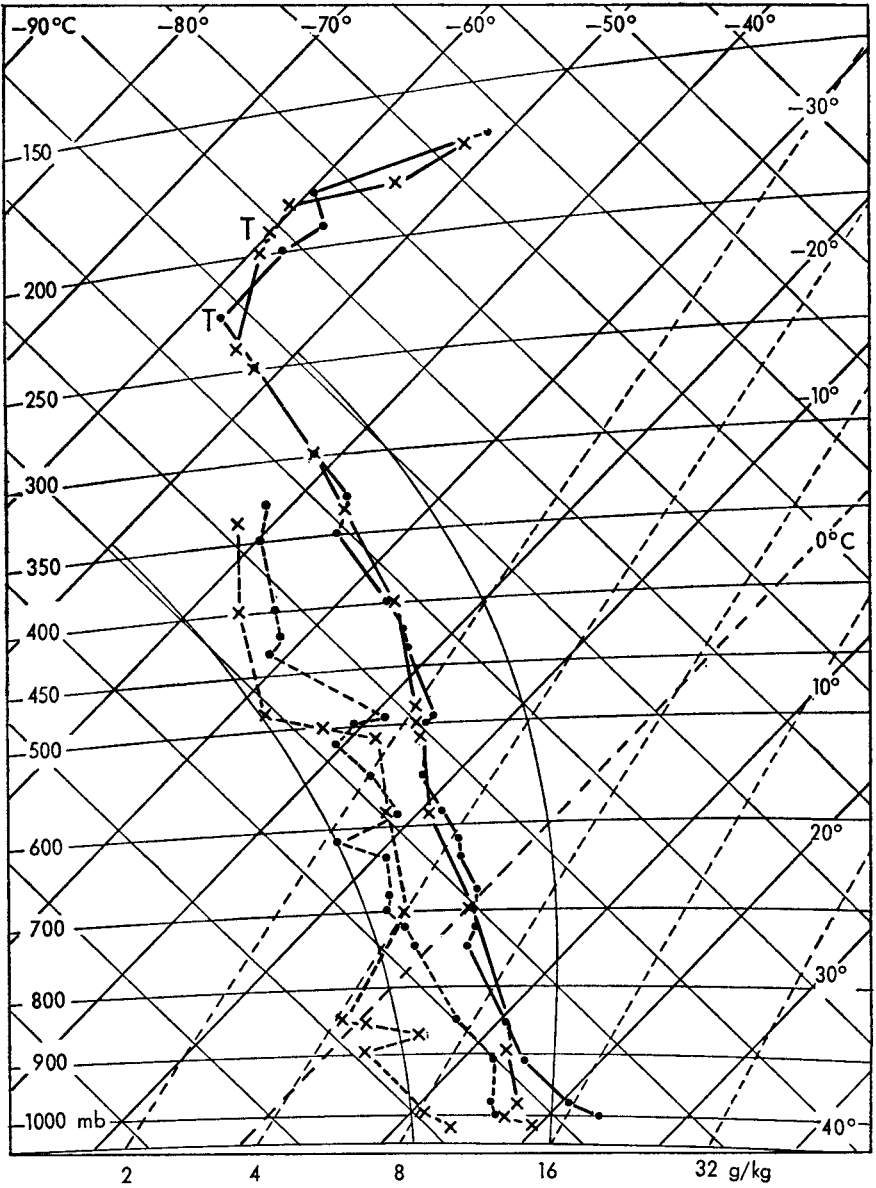


FIGURE 5—CRAWLEY AND HEMSBY TEPHIGRAMS FOR 11 GMT, 26 JUNE 1973

- — ● Crawley dry-bulb temperature
- - - - ● Crawley dew-point temperature
- × — × Hemsby dry-bulb temperature
- × - - - × Hemsby dew-point temperature
- T Tropopause

(See, for example, Newton,⁷ Carlson and Ludlam,⁸ Browning,^{5, 6} and Hardman.⁹) However, in some previous severe storm and tornado situations (e.g. Roach¹⁰ and Lamb^{11, 12}) this stable layer has not been in evidence, and it seems that it is not such an important prerequisite for tornadoes in this country as it is in the United States. There is no reason to suppose that the Crawley and Hemsby tephigrams are unrepresentative of conditions in the Cranfield area before the storm's approach. Cranfield was sufficiently far south of the Durham-Pembroke frontal zone and rain-area to be in the same air mass as Crawley and Hemsby, the Wash-Dorset front being only a surface feature.

Movement of the storm cells. The motion of the storm cell which caused the Cranfield tornadoes is shown in Figure 6. This shows successive positions of the PPI radar echo observed from the Royal Radar Establishment at Malvern and determines the speed of the storm as about 20 kt from a direction of 230°. It can be seen from Figure 7, which gives the Crawley and Hemsby hodographs for 12 GMT, that this does not correspond with the tropospheric wind at any level. The storm appears to have been organized on the lines of the 'SR' model proposed by Browning,^{5, 6} with substantial inflow from the rear and right of the storm at middle levels, but with little or no deviation in direction from that of the mid-tropospheric wind. The echo observed by the highest-elevation radar beam at 1304 GMT, the time of the second tornado at Cranfield, was of remarkable intensity. Its south-eastern edge was approximately over Cranfield and it extended some 17 miles to the north-west. Unfortunately the storm was too far from Malvern for a reliable estimate to be made of its height. There is no evidence of a hook echo.

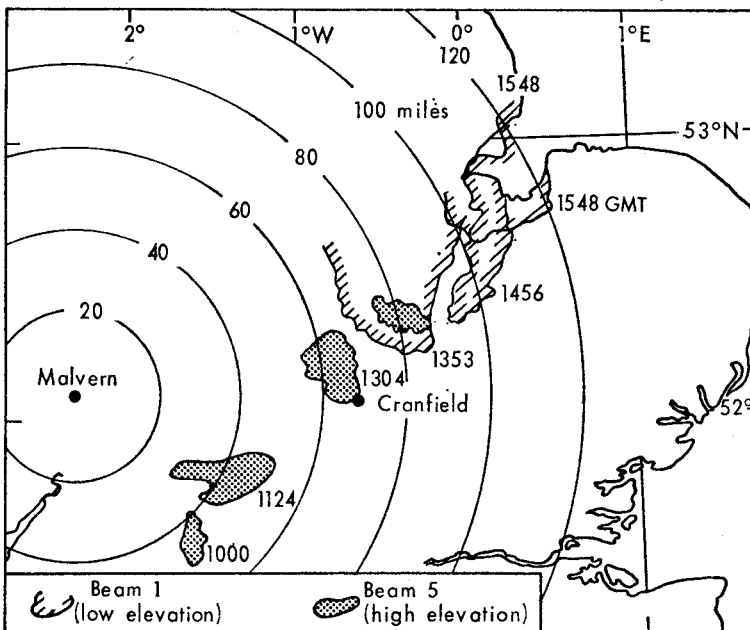


FIGURE 6—SUCCESSIVE POSITIONS OF THE RADAR ECHO FROM THE STORM WHICH PRODUCED THE CRANFIELD TORNADOES

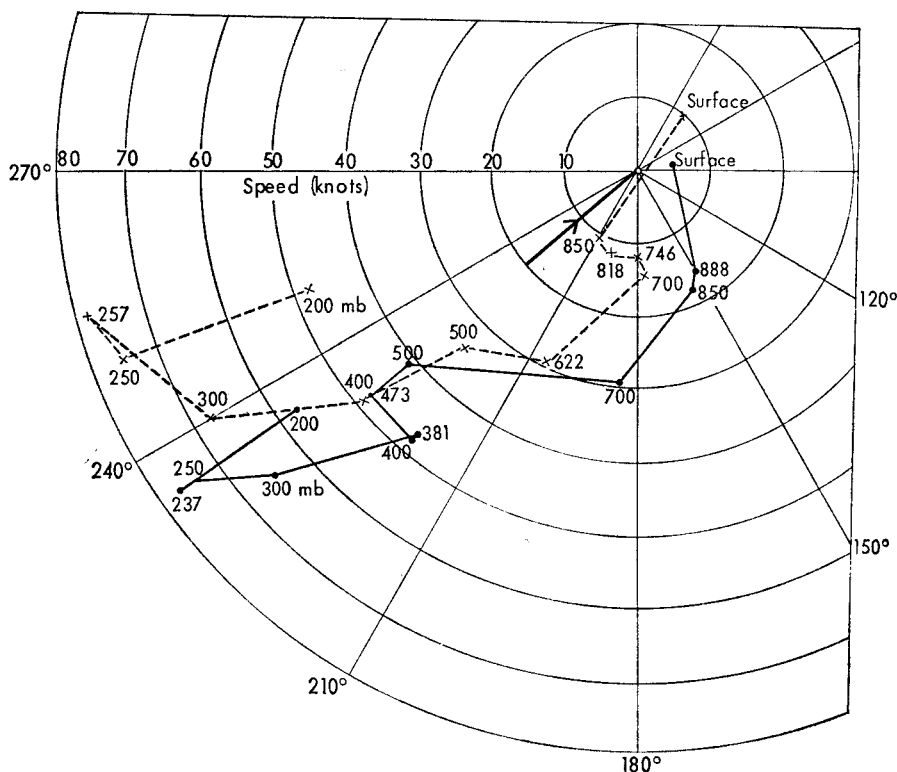


FIGURE 7—HODOGRAPHS FOR 12 GMT ON 26 JUNE 1973

● — ● Crawley × --- × Hemsby

The bold arrow shows the velocity of the storm which produced the Cranfield tornadoes.

The Cranfield tornadoes occurred in the typical position (see, for example, Ludlam¹³) at the forward right flank of the storm. This is confirmed by the rainfall analysis. The autographic records from the recording rain-gauges in the area showed that the total rainfall from this storm was as shown in Figure 8. It remained dry at Cranfield itself but there was heavy rain less than a mile to the north-west. Farther north there were several reports of hail and the Royal Aircraft Establishment (RAE) at Bedford (13 miles north-north-east of Cranfield) reported heavy hail with large hailstones (1½–2 cm in diameter) for 10 minutes between 1315 and 1330 GMT. The storm's gust front gave rise to maximum gusts of 42 kt at RAE Bedford at 1325 GMT and 51 kt at Wyton (28 miles north-east of Cranfield) at 14 GMT, and by 1548 GMT the storm cell was situated over the area around the Wash and was still active enough to give 11 mm of rain in just over an hour at Wisbech.

At the time when the storm which produced the Cranfield tornadoes was moving away over the Wash, a continuous line of precipitation including several distinct cells was oriented north-south from near Lincoln to south of Bedford. The Malvern radar had now ceased operation but the line of storms could be followed (though with poorer definition) by referring to film from the Eastern Air Traffic Control Radar at RAF Watton in Norfolk. This showed

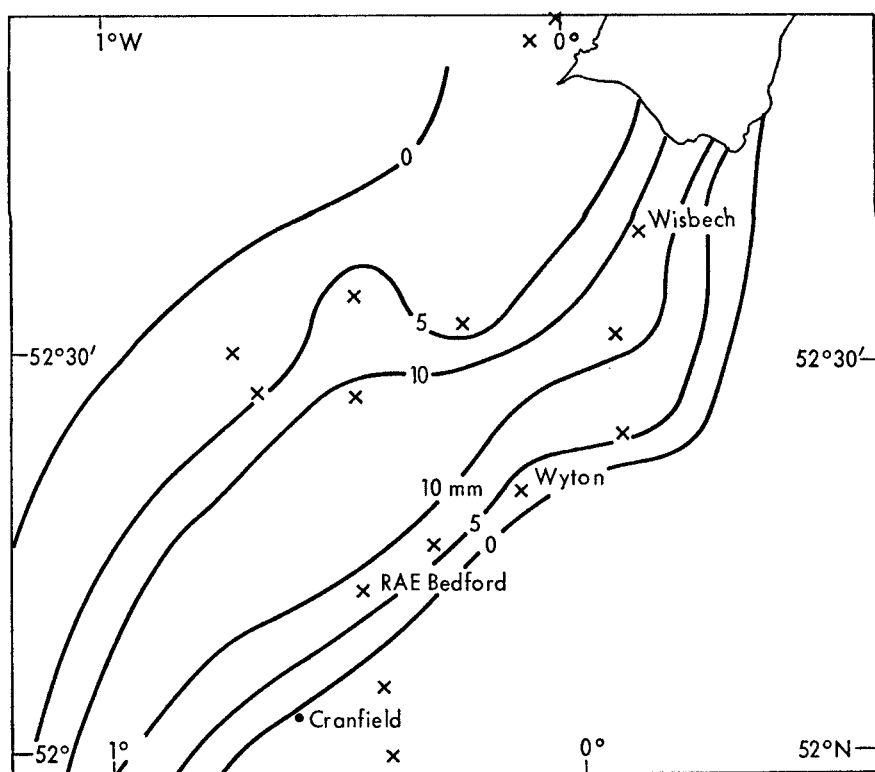


FIGURE 8—RAINFALL FROM THE STORM WHICH PRODUCED THE CRANFIELD
TORNADOES ON 26 JUNE 1973

The positions of autographic rain-gauges are marked by crosses. The records from four autographic rain-gauges outside the area of the map were used to assist in drawing the isohyets.

that one cell in this line was in a position to cause the tornadoes at Parson Drove and Tydd St Giles if these had occurred on its right flank shortly after 17 GMT, the time at which they are reported to have caused damage. So this second outbreak seems to have been caused by another severe storm of the wind-shear type, but there is no evidence this time of any convergence line or topographic stimulus for the tornado formation.

The total rainfall for the 24-hour period from 09 GMT on 26 June is shown in Figure 9. This is a combination of the rainfall from several storms which occurred during the afternoon and evening and shows how they followed much the same south-west to north-east track.

Comparisons with similar situations. The causes of tornadoes are still imperfectly understood. A favourable vorticity field and strong convection are obviously required, and Foster¹⁴ has proposed a predictive index for the United States which is a combination of 'vorticity acceleration' and air-mass instability. A further requirement for tornado generation seems to be the persistence of vigorous convection over a sufficiently long period, so it is only in the 'severe mature' stage of Browning's model^{15, 6} that tornadoes can be expected to occur. The importance of 'steady-state' convection is evidenced by the formation of

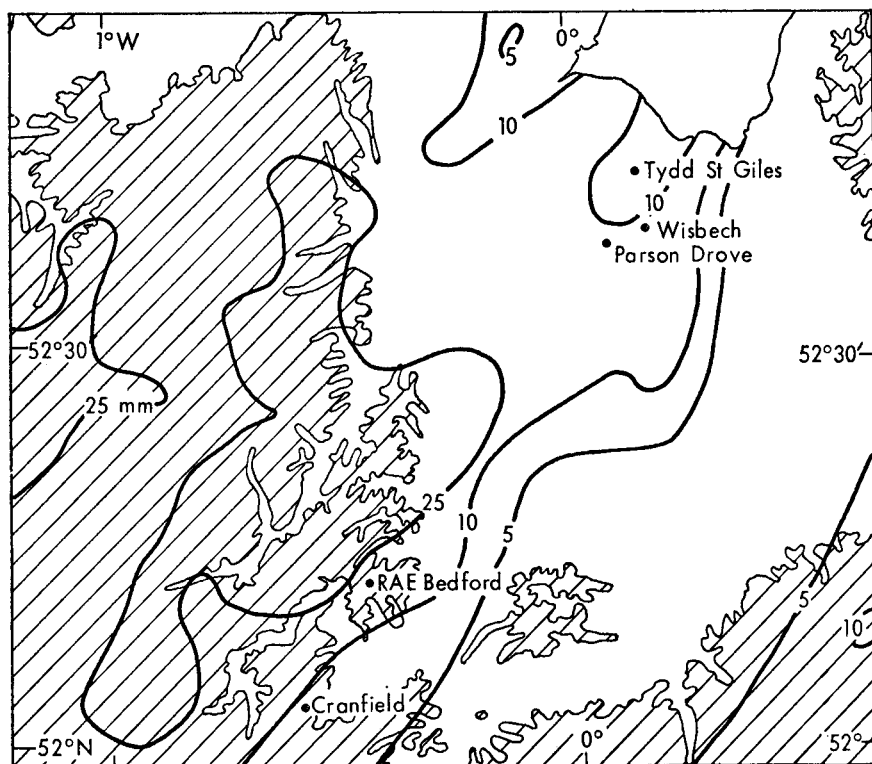


FIGURE 9—TOTAL RAINFALL FOR 24 HOURS FROM 09 GMT ON 26 JUNE 1973
Isohyets are given for 5, 10 and 25 mm. Shading represents land over 200 ft in altitude.

vortices under the cumulus which developed as a result of the *Torrey Canyon* fire¹⁵ and in comparable circumstances elsewhere, for example, the Surtsey volcanic eruption.¹⁶

Tornadoes are by no means as infrequent in Britain as is generally supposed. Lacy¹⁷ listed 78 observations on 36 days in four years, and others must presumably have gone unrecorded. However, the overwhelming majority of these were not connected with severe storms and many not even with thunderstorms. Most of these tornadoes were of course comparatively minor phenomena, being not especially violent, causing no great damage and rapidly dissipating. The really destructive tornadoes are generally associated with cumulonimbus clouds, and in particular with severe local storms. These occurrences are comparatively rare in this country, but several have been well documented in the past and have shown certain similarities to the subject of the present investigation.

Lamb^{11, 12} has described in great detail the events of 21 May 1950, when three tornadoes occurred in much the same area as those of 26 June 1973, and two of these in fact passed within five miles of Cranfield. Though the mesoscale frontal structure and pressure distribution as analysed by Lamb are both very complicated, the situation in eastern England is really quite similar with a surface trough oriented from south-west to north-east dividing easterlies from north-easterlies and upper flow which was clearly south-westerly.

The situation just before the Horsham storm on 5 September 1958^{18, 19} showed a distinct line of convergence from the Wash to Portsmouth. In the south the winds on either side of this line were from the north and east, while the upper flow was from slightly west of south. The storm moved north-eastwards, giving rise to a tornado on its right flank opposite the region of heaviest hail near Horsham. The London storm of 27 June 1947²⁰ occurred in somewhat similar circumstances. There was a weak north-west wind at the surface, spreading from the Midlands with frontogenetic action near the east coast. The 700-mb flow was southerly and winds at Larkhill were southerly up to 450 mb. The storm gave a maximum gust at Croydon of 64 kt and there was a report of a tornado at Colchester, though this appears to have been comparatively weak.

With the Wiltshire hailstorm of 13 July 1967⁹ there was strong vertical wind shear but no definite convergence line at the surface. The nature of the wind damage gave indirect evidence of a tornado although no tornado was actually observed. Roach¹⁰ states that the Barnacle tornado of 21 April 1968 was the result of 'a wind-shear' storm organized on the lines of Browning and Ludlam;²¹ here the storm occurred some 35 miles behind the main surface convergence zone, but was triggered by an advancing cold front. The south Yorkshire tornado of 26 September 1971 described by Wright²² was also associated with a thunderstorm in an area of vertical wind shear, though it is doubtful whether this storm could be classed as a severe local storm in Browning's sense.

Conclusions. Evidently the Cranfield tornadoes were associated with a severe storm of the wind-shear type. The Tydd St Giles and Parson Drove tornadoes resulted from a different storm, which was similar to the first and followed a parallel track. Both occasions were typical in that the tornadoes occurred on the right flank (i.e. to the south-east) of the parent storms.

Comparable synoptic situations have given rise to severe storms and tornadoes in the past, though no investigation has been made of occasions which were apparently favourable for the occurrence of severe travelling storms but when they failed to develop, or of severe storms, such as the Wokingham storm of 9 July 1959,²¹ which had no associated tornado.

The advice of Miller and Starrett,²³ that tornadoes should be predicted in exceptionally severe thunderstorm situations, may be debatable, but there is no doubt that the events of 26 June 1973 emphasize again the risk of tornadoes occurring in these circumstances.

Acknowledgements. The Environmental Sciences Research Unit (College of Aeronautics, Cranfield) and the Building Research Establishment, Garston, Herts., gave much useful assistance, and various authorities co-operated in providing autographic wind and rainfall records.

REFERENCES

1. FUJITA, T. T.; Proposed characterization of tornadoes and hurricanes by area and intensity. University of Chicago Department of Geophysical Sciences. *SMRP Res Pap*, No. 91, Chicago, 1971.
2. HEMENS, L. G.; Whirlwind at Shoeburyness. *Met Mag, London*, **79**, 1950, pp. 256-260.
3. TAGG, J. R.; Tornado at Cranfield—26 June 1973. *Weather, London*, **29**, 1974, pp. 60-63.
4. EATON, K. J. and JUDGE, C. J.; Tornado damage to buildings, 26 June 1973. Garston, Building Research Establishment (in course of preparation).
5. BROWNING, K. A.; The evolution of tornadic storms. *J Atmos Sci, Lancaster, Pa*, **22**, 1965, pp. 664-668.
6. BROWNING, K. A.; The organization of severe local storms. *Weather, London*, **23**, 1968, pp. 429-434.

7. NEWTON, C. W.; Dynamics of severe convective storms. *Met Monogr, Boston*, 5, 1963, No. 27, pp. 35-58.
8. CARLSON, T. N. and LUDLAM, F. H.; Conditions for the occurrence of severe local storms. *Tellus, Stockholm*, 20, 1968, pp. 203-226.
9. HARDMAN, M. E.; The Wiltshire hailstorm, 13 July 1967. *Weather, London*, 23, 1968, pp. 404-415.
10. ROACH, W. T.; The Barnacle tornado. *Weather, London*, 23, 1968, pp. 418-423.
11. LAMB, H. H.; Tornadoes of 21 May 1950. *Met Mag, London*, 79, 1950, pp. 245-256.
12. LAMB, H. H.; Tornadoes in England, 21 May 1950. *Geophys Mem, London*, 12, No. 99, 1957.
13. LUDLAM, F. H.; Severe local storms: a review. *Met Monogr, Boston*, 5, 1963, No. 27, pp. 1-32.
14. FOSTER, D. S.; Relationship among tornadoes, vorticity acceleration, and air mass stability. *Mon Weath Rev, Washington, D.C.*, 92, 1964, pp. 339-343.
15. HARPER, J. F.; The Torrey Canyon smoke plume (photographs). *Weather, London*, 22, 1967, pp. 368-369.
16. THORARINSSON, S. and VONNEGUT, B.; Whirlwinds produced by the eruption of Surtsey volcano. *Bull Amer Met Soc, Lancaster, Pa*, 45, 1964, pp. 440-444.
17. LACY, R. E.; Tornadoes in Britain during 1963-6. *Weather, London*, 23, 1968, pp. 116-124.
18. LUDLAM, F. H. and MACKLIN, W. C.; The Horsham hailstorm of 5 September 1958. *Met Mag, London*, 89, 1960, pp. 245-252.
19. ROWSELL, E. H.; Storms of 5 September 1958, over south-east England. *Met Mag, London*, 89, 1960, pp. 252-257.
20. DOUGLAS, C. K. M. and LEWIS, L. F.; Thunderstorms of 27 June 1947. *Met Mag, London*, 76, 1947, pp. 179-185.
21. BROWNING, K. A. and LUDLAM, F. H.; Airflow in convective storms. *QJR Met Soc, London*, 88, 1962, pp. 117-135.
22. WRIGHT, R. B.; A tornado in south Yorkshire and other tornadoes in Britain. *Weather, London*, 28, 1973, pp. 416-428.
23. MILLER, R. C. and STARRETT, L. G.; Thunderstorms in Great Britain. *Met Mag, London*, 91, 1962, pp. 247-255.

551.515.8:551.543

RAPID PRESSURE RISE FOLLOWED BY AN OSCILLATION OF PRESSURE DURING THE PASSAGE OF A TROUGH AT LIVERPOOL AIRPORT ON 5 DECEMBER 1972

By J. A. YOUNG
(Meteorological Office, Liverpool Airport)

Summary. On 5 December 1972 a pressure rise of 3 mb to $3\frac{1}{2}$ mb in around 30 minutes occurred at Valley and Blackpool in association with a marked trough moving eastwards. As the trough crossed the Liverpool and Manchester areas the pressure rise became even more rapid and was followed by an oscillation of pressure. The synoptic situation on 5 December 1972 suggested that an upper-level disturbance was relevant to this occurrence.

Introduction. A marked trough passed through Liverpool at about 1925 GMT on 5 December 1972 and was followed by a rapid pressure rise (3 mb in 25 minutes). After reaching the peak of the rise the pressure fell again even more rapidly (0.8 mb in 2 minutes) before rising again more slowly and eventually levelling off (see Figure 1).

This appeared to be an unusually large rate of change of pressure and it was decided to compare it with changes due to this trough recorded at other stations.

Synoptic situation. The surface analysis for 12 GMT on 5 December 1972 showed a vigorous depression just west of the Hebrides and its associated cold front lying north-north-east-south-south-west, just to the west of Liverpool. The front cleared Liverpool at about 13 GMT and during the afternoon it continued to move quickly eastwards; by 18 GMT it was lying from the Wash

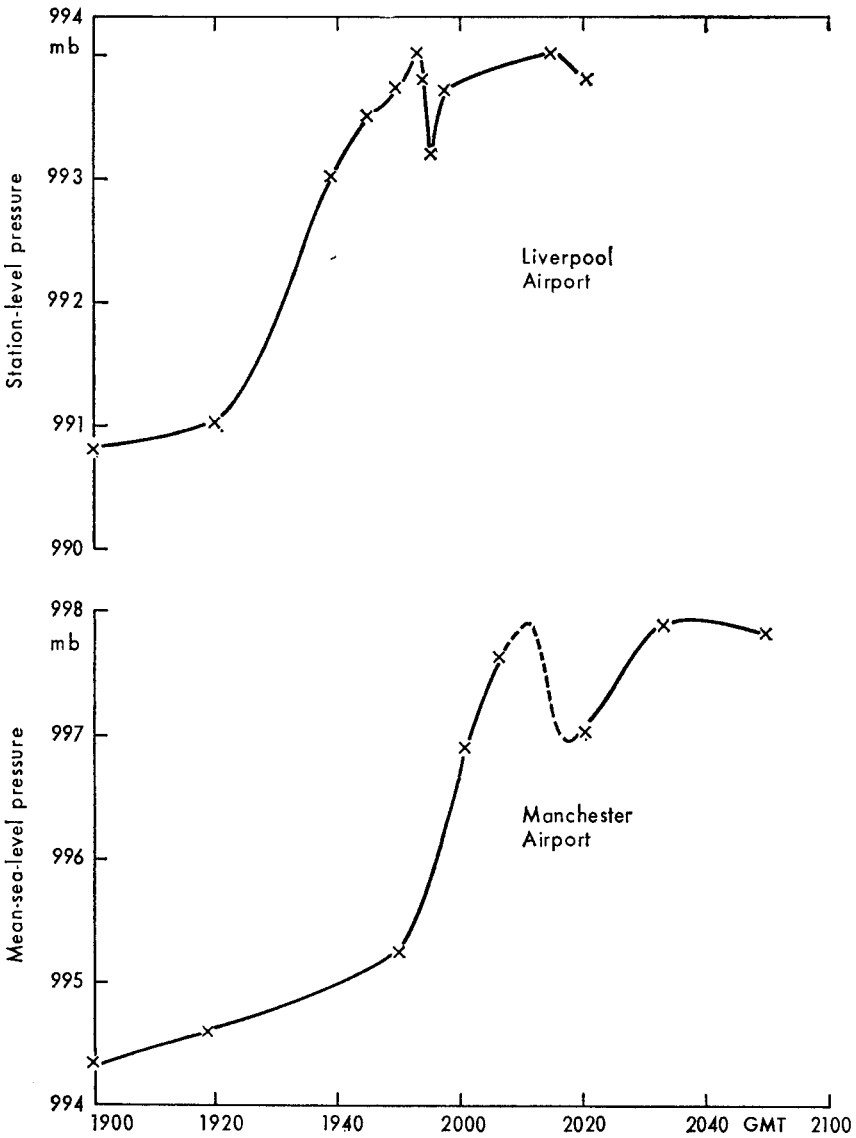


FIGURE 1—GRAPHS OF PRESSURE CHANGES AGAINST TIME FOR PRESSURE CHANGE ON TROUGH

On the graph for Manchester Airport the pecked part of the trace is the suggested shape based on the barogram (no readings were taken between 997.6 mb at 2007 GMT and 997.0 mb at 2020 GMT).

to the Isles of Scilly (see Figure 2). The depression moved north-eastwards at about 40 kt* during the afternoon, and an associated trough moved eastwards at about 30 kt across Scotland, Ireland and the Irish Sea, and was lying from Anglesey to Morecambe Bay at 18 GMT (see Figure 2). It was this trough which was associated with the marked pressure change.

An upper trough moved eastwards across the British Isles ahead of the surface frontal system, followed closely by a westerly upper jet stream (at around 300 mb) which gradually increased in strength as it extended across the British Isles.

Comparison of pressure changes at Liverpool with those at other stations. Details of rainfall, temperature, pressure and surface wind associated with the passage of the trough at various stations are shown in Figure 3 and in Table I. Similar details for Ronaldsway, Isle of Man, showed no evidence of a trough.

TABLE I—DETAILS OF SURFACE WIND ASSOCIATED WITH PASSAGE OF TROUGH

Station	Details of surface wind	
	<i>degrees</i>	<i>knots</i>
Valley	230	23, gusts 35, with abrupt veer at 1747 GMT
	to 290	20, gusts 37
Blackpool Airport	230	20, gusts 29, with abrupt veer at 1825 GMT
	to 270	17, gusts 28. Isolated gust 43 kt at 1825 GMT
Liverpool Airport	230	20, gusts 32, with abrupt veer at 1923 GMT
	to 300	23, gusts 36
Manchester Weather Centre	230	20, gusts 38, with abrupt veer at 1945 GMT
	to 290	19, gusts 36
Manchester Airport	250	25, gusts 35, with abrupt veer at 1948 GMT
	to 310	20, gusts 34. Isolated gust 42 kt at 1920 GMT

These details refer to the 30 minutes on either side of the time of passage of the trough with directions in degrees true. The values for the gusts are the highest speeds reached at least five times in the 30 minutes.

The pressure rise. A pressure rise of $3\text{--}3\frac{1}{2}$ mb occurred at all the stations shown in Figure 2, but at Valley and Blackpool it was not as rapid as at the other three stations.

A general slow and gradual rise of pressure occurred over Ireland behind the trough. These rises became more pronounced after 16 GMT as the depression moved north-eastwards away from northern Scotland with a maximum rise at around the time when the trough crossed the Liverpool area.

Much larger rises of pressure occurred over Scotland (in the range 6 mb to 9 mb in 3 hours) associated with the movement of the depression, but they were not so steep as those which occurred at Liverpool and Manchester on the trough.

The latter particularly rapid rise may be explained by a small rise due to the passage of the trough coinciding with a more general rise over the west of the British Isles due to the movement of the depression.

The oscillation of pressure. This was the most striking feature of the pressure change at Liverpool Airport (and the initial spur to the preparation of this report). The fall of pressure after the peak of the original rise was even more rapid than the rise itself, followed by a more gradual rise up to the value of the original peak. The barograms for Manchester Weather Centre and

* 1 kt $\approx$ 0.5 m/s.

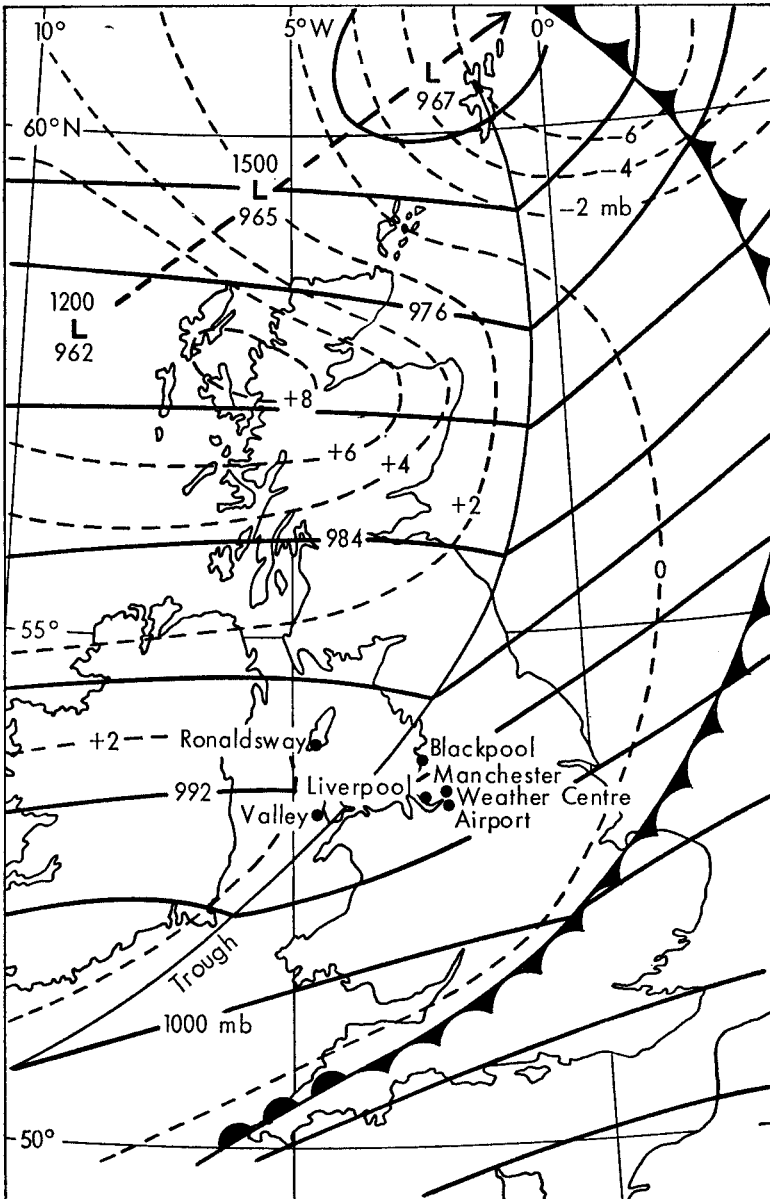
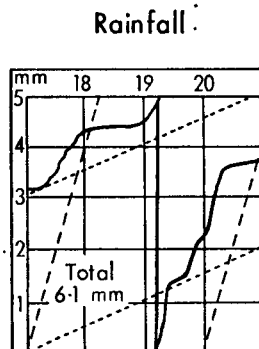
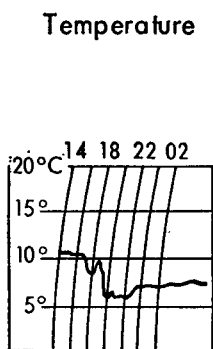
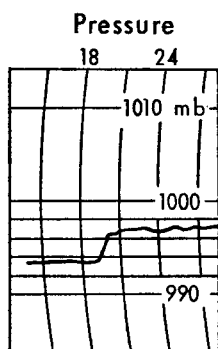


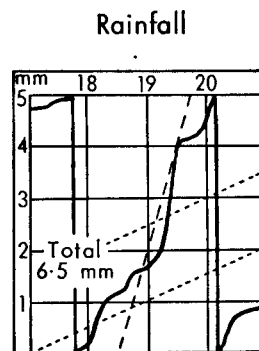
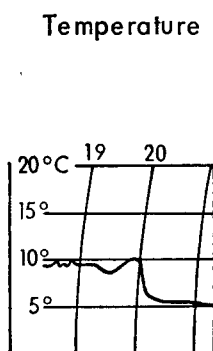
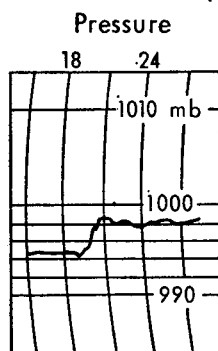
FIGURE 2—SURFACE ANALYSIS FOR 18 GMT ON 5 DECEMBER 1972

The dashed lines are isallobars (lines of equal pressure tendency) in whole millibars per 3 hours at 2-mb intervals. Positions of centres at 12 and 15 GMT are also indicated.

Manchester Weather Centre



Manchester Airport



Valley

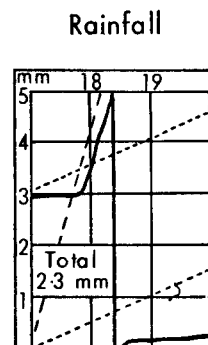
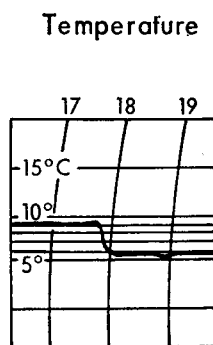
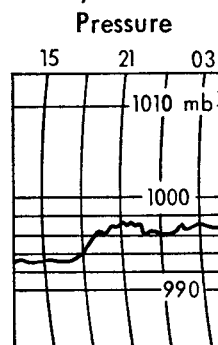
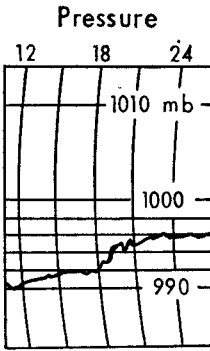


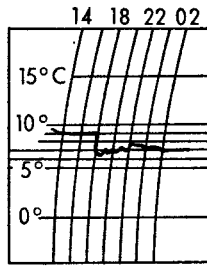
FIGURE 3—DIAGRAMMATIC REPRESENTATIONS OF PRESSURE, TEMPERATURE AND RAINFALL TRACES ASSOCIATED WITH PASSAGE OF TROUGH

All chart times are GMT. On the rainfall charts the pecked lines indicate an intensity of 4 mm/h and the dotted lines one of 0.5 mm/h.

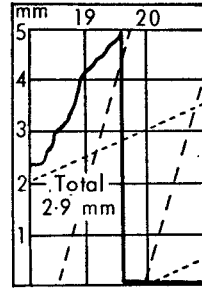
Blackpool



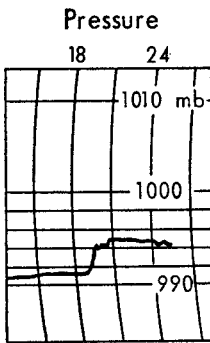
Temperature



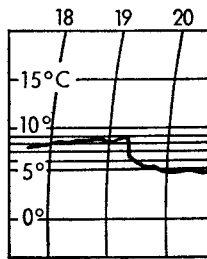
Rainfall



Liverpool Airport



Temperature



Rainfall

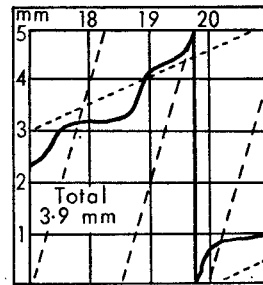


FIGURE 3—continued

Preston also showed a similar oscillation, as did the readings from Manchester Airport. The graph of pressure against time at Liverpool and Manchester Airports, based on their observed readings, is shown in Figure 1. Valley and Blackpool Airport showed no evidence of such an oscillation.

To summarize the pressure changes at Liverpool with those at other stations: all the stations shown in Figure 2 showed a rapid rise of pressure; no oscillation showed at Valley or at Blackpool; the Preston barogram showed an oscillation, and a quite marked oscillation occurred at Liverpool and Manchester.

Factors which may be relevant to the occurrence. There is no evidence that this occurrence was associated either with an inversion or with thundery activity, but there was an upper jet stream (around 300 mb) close to the area.

The oscillation in the rising pressure appeared at the Manchester Airport office almost exactly 20 minutes after the same phenomenon appeared at Liverpool Airport. On the assumption that it occurred along a line orientated roughly north to south (it also showed up on the Preston barogram) this gives a speed of movement of 63 kt between Liverpool and Manchester Airports. This fits in with the winds shown on the 12 GMT and 18 GMT soundings from Aughton (60–70 kt from 850 mb to 700 mb, with a steady increase above 700 mb up to the jet-stream maximum of 120 kt at around 300 mb). An

upper-level disturbance would, therefore, seem relevant to this occurrence, since wind speeds were high, with fairly large fluctuations, at all levels throughout the day.

Final comments. The barograms for Liverpool Airport for the years 1960 to 1972 were studied for rapid pressure changes (3 mb or more in less than 30 minutes being considered) and also for signs of oscillation after such a change. The barogram for 5 December 1972 was then superimposed on any barogram with such a change in order to compare the rates of change. These comparisons are summarized as follows:

- (a) There were seven occasions of frontal rates of change equal to or greater than that of the trough in question. All were rises of pressure.
- (b) Several cases of changes of between 2 mb and 5 mb in 20 minutes or less occurred in association with thunderstorms observed at the station, some of which were very erratic, but no definite oscillation was noted.
- (c) There were six cases which showed signs of an oscillation after a rapid change of pressure (considering either a rise or a fall) in association with either a front or a trough. The rate of change in all these cases was less than that of the trough in question, and none of the cases in (a) above was followed by an oscillation.
- (d) The most noteworthy feature of the trough in question was that the pressure rise occurred suddenly after several hours of almost uniform pressure. It was the only such case at Liverpool in the 12 years considered.

Occurrences of this kind are not uncommon, but the magnitude of the rise following several hours of uniform pressure makes it noteworthy.

On the evidence available it would seem that this phenomenon was due to an upper-level disturbance.

Acknowledgement. The author would like to thank his colleagues for their help in preparing this article, especially Mr H. T. D. Holgate and Mr T. H. Kirk for their advice and suggestions as to its presentation.

REVIEW

Comparison between pan and lake evaporation, WMO Technical Note No. 126, by C. E. Hounam. 270 mm × 210 mm, pp. 52, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1973.

A reliable means of assessing water loss from reservoirs by evaporation has long been sought by water supply undertakings. Trustworthy evaporation data are also important for the planning, design and operation of irrigation and drainage facilities, navigation canals and other open water systems. The cheapest and simplest technique employs a pan (or tank), a water-level measure and a rain-gauge.

It is clear that the rate of evaporative water loss from a small, shallow tank will not be the same as from a large and relatively deep lake. The large water mass in the lake has a capacity to store heat which is not shared by the small sample of water in the tank, where changes of temperature will be, by comparison, both large and rapid. There are also other important differences involving friction, absorption and reflection of radiation, and lake-induced

microclimatic effects. Mr Hounam, an acknowledged authority on the subject, deals expertly and simply with present practices for using pans to monitor large-scale water loss by evaporation.

After a brief but comprehensive introduction to most of the types of pan or tank currently in use, the author deals with the important problem of siting the pan in relation to the lake (with an unfortunate printer's omission from para. 3.3.). He then discusses the effects of inflow, outflow, lake dimensions and surface wind waves. Attention is drawn to the importance of differences between the way in which radiation is absorbed and reflected by the lake and by the pan, and also to the differences between friction over the large water surface and the smaller, land-enclosed one.

The lake's own microclimatic effects are examined and also the difficulties experienced in obtaining true values of evaporation from pan and lake for the determination of 'lake-to-pan' coefficients. Coefficients for a selection of tanks and locations are listed and the well-known earlier *Technical Note* No. 83 is cited. Seasonal and spatial variations of coefficients are shown. The indirect Russian method employing both a small and a large tank is explained and also the use of floating tanks. Details are given of techniques involving the American Class A pan, an evaporimeter normally exposed on a stand, whereas most others are buried in the ground to within a few centimetres of their rims.

The collection and use of relevant meteorological data are summarized. The conclusions are realistic and are frankly presented; there is no attempt to avoid serious unsolved problems.

B. G. WALES-SMITH

Synoptic climatology: Methods and applications, by R. G. Barry and A. H. Perry. 240 mm × 160 mm, pp. xvi + 555, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London EC4P 4EE, 1973. Price: £6.50.

The authors of this book have, I think, had the praiseworthy aim of providing a basic course-book on the subject. They recognize it as not being a 'neat coherent field' and give one of its basic functions as the study of 'the nature of the relationships between atmospheric circulation systems and weather conditions, especially in particular geographical locations'. They have provided a very wide-ranging survey of the subject and offer much material for thought. Included along with well-established concepts are many of a highly speculative nature and it is not always made clear which is which. It is true the source of these latter ideas is always given in the very large bibliography, but many readers will not have access to the source papers. This procedure of including every opinion that has found its way into print may be acceptable in a review article but seems to me inappropriate in what is conceived as a textbook.

There are five sections, entitled: The basic data and their analysis; Synoptic climatological analysis; Statistical methods; Applications; Synoptic climatology; Status and prospects.

The first section contains matter which can mostly be found in standard texts on meteorology. The second contains a thorough description of methods of weather-type classification which, of course, is a vital element in the methodology of the subject. (It is a pity that the Baur-Hess-Brezowsky type HN was rendered into English, on page 123 and in Figure 3.13(c) as 'High over the North Sea' when the intention of the catalogue-makers was clearly 'High over

the Norwegian Sea'—a very different situation.) In a natural desire to give some order to the subject they say on page 88 that 'the Icelandic low at the surface is represented by the mean 500 mb trough over Eastern North America'. In the context of westward-sloping axes of synoptic systems with height, this view is so improbable an idea that it should not be slipped into a textbook without a great deal more discussion.

Not being an expert on statistics I cannot comment on the quality of the section on statistical methods, but I would prefer to see students referred to one or two suitable texts on statistics rather than being offered a compressed review which does not even include such fundamental items as significance levels for correlation coefficients or the other basic tests such as 'Student's' t , F -test, etc.

In the section 'Applications' the authors discuss the vexed matter of 'Singularities'. They start by noting the evidence against their reality but end up by describing other work with somewhat uncritical fervour.

Climatic change is also treated in this section; and despite the authors' attempt to create a sensible picture the scene remains very confused. The confusion will not be lightened by an unfortunate misprint on the third line of page 378, where ^{18}O has become 180 in a reference to the amount of oxygen isotope (^{18}O) in the ice core retrieved in north-west Greenland in 1966. There is also a reminder that it is not only changes of circulation type which lead to secular changes in temperature but that there are changes in temperature within a circulation type from one epoch to another.

The 'quasi-biennial oscillation' and solar-terrestrial relationships are helpfully discussed, and the small amplitude of both effects is stressed. The authors do not, surprisingly, do this in discussing lunar-weather relationships.

There is an enormous amount of interesting and thought-provoking material in these 450 pages but as said earlier its quality is mixed, and I feel that it is expecting too much of students to expect them to exercise so much discernment.

The book is very nicely printed and the diagrams are abundant and (with a very few exceptions) exceptionally clear and easy to read.

M. K. MILES

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki:

Meteorologika 23: *Weather-types and sunshine-duration in the west coast of the Aegean Sea*. By A. A. Flocas and P. J. Pennas. 1972.

Meteorologika 24: *Ground surface temperature*. Part II. Grass-covered ground. By G. C. Livadas and Y. A. Goutsidou. 1973.

Meteorologika 26: *Atmospheric-pressure in Thessaloniki—Greece*. By G. C. Livadas and T. J. Makroyannis. 1973.

Meteorologika 27: *Cloudiness in the major area of Thessaloniki*. By V. A. Angouridakis. 1973.

Université de Thessaloniki. *Annuaire de l'Institut Météorologique et Climatologique*, 39. Observations Météorologiques de Thessaloniki 1970, publiées par le Prof. Dr. G. C. Livadas, Thessaloniki, 1973.

Université de Thessaloniki. *Annuaire de l'Institut Météorologique et Climatologique*, 40. Observations Météorologiques de Thessaloniki, 1971, publiées par le Prof. Dr. G. C. Livadas, Thessaloniki, 1973.

Université de Thessaloniki. *Annuaire de l'Institut Météorologique et Climatologique*, 41. Observations Météorologiques de Thessaloniki, 1972, publiées par le Prof. Dr. G. C. Livadas, Thessaloniki, 1973.

551.515.33

LETTER TO THE EDITOR

The Thorpe Bay-Foulness tornado

Mr C. I. Griffiths, in his interesting account of the south-east Essex tornado,¹ suggests that the phenomenon may have been initiated by heated effluent from a power station situated some 15 miles upwind from the initial region of wind damage. From my study of funnel-cloud formation to the lee of factory chimneys (which the author refers to in his paper) it appears that these vortices are relatively weak and generally short-lived, and so would be unlikely to produce winds of tornado strength even if they were able to retain their identity whilst travelling for some 30 minutes from source. Maximum surface-wind velocities appear to be somewhat less than those reported by Heighes² near the cores of aircraft-wing vortices.

Conditions were favourable on 7 August 1973 for heavy shower activity with strong downdraughts, and the Shoeburyness anemogram suggests the passage of a gust front. This may well have been associated with an active part of a secondary cold front which was crossing the area at about the time of the tornado. Broadly similar conditions were discussed by Goldie and Heighes³ after studying a North American tornado. Also, in an experiment described elsewhere,⁴ an artificial 'micro' gust front was found to initiate weak vorticity, as cold air moved over a warmer water surface.

J. M. HEIGHES

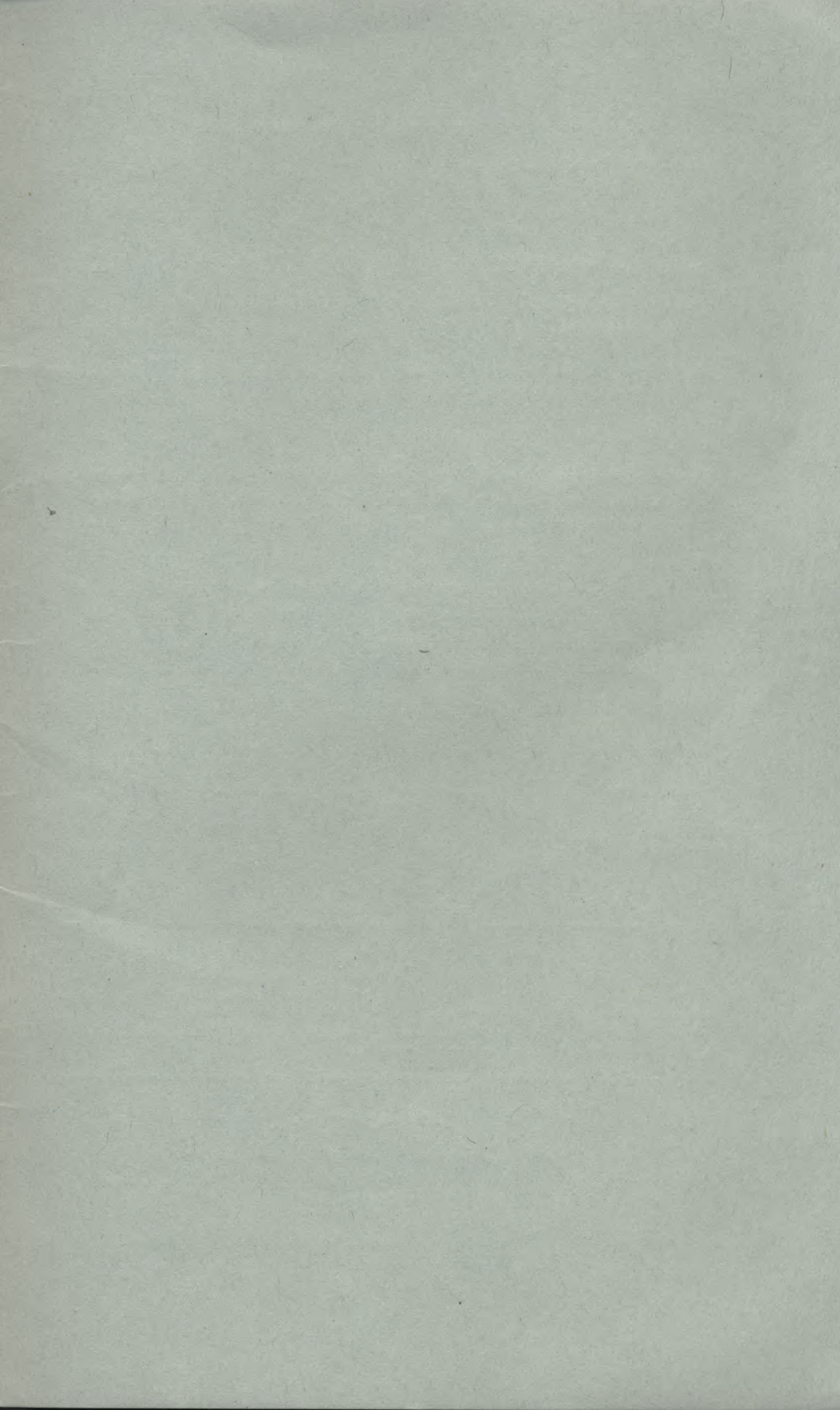
Jomar,
College Road,
Sandhurst,
Berkshire

REFERENCES

1. GRIFFITHS, C. I.; Tornado in south-east Essex on 7 August 1973. *Met Mag, London*, 103, 1974, pp. 49-52.
2. HEIGHES, J. M.; Vortices. *New Scientist, London*, 55, 1972, pp. 108-109.
3. GOLDIE, E. C. W. and HEIGHES, J. M.; Investigation of a United States Midwest tornado. *Met Mag, London*, 101, 1972, pp. 270-278.
4. HEIGHES, J. M.; Comment on 'steam devils' over Lake Michigan during a January arctic outbreak. *Mon Weath Rev, Washington, D.C.*, 100, 1972, p. 750.

CORRECTION

Meteorological Magazine, February 1974, p. 49. In the second line of the Summary 'downwind' should read 'upwind'.



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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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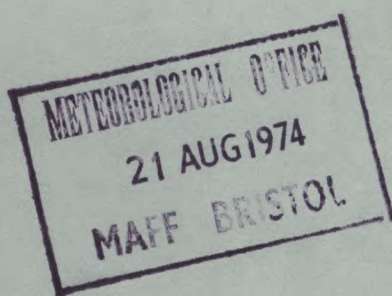
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THE CONTRIBUTION OF SATELLITES TO THE EXPLORATION OF THE GLOBAL ATMOSPHERE AND TO THE IMPROVEMENT OF WEATHER FORECASTING*

By B. J. MASON

Summary. Artificial satellites have been assisting weather forecasters for 14 years. Whilst originally satellites were simply used for pictorial representation of cloud distribution, their use has extended via the remote measurement of temperatures of land, sea and cloud surfaces to the reconstruction of complete vertical distributions of temperature and humidity. Together with their usefulness in communicating with automatic weather stations, weather satellites will become major components in any global weather-observing and communication system of the future.

Introduction. Satellites are already playing an important role in observing the weather on a global scale. During the last 14 years the U.S.A. have launched 22 operational polar-orbiting meteorological satellites in the TIROS, ESSA andITOS series, together with five large NIMBUS research vehicles and two geo-stationary satellites that are largely devoted to meteorology. Having obtained cloud pictures and radiometric data on an experimental basis from COSMOS satellites since 1966, the U.S.S.R. launched the first of its operational METEOR weather satellites in 1969. So far the emphasis has been on obtaining cloud pictures in both visible and infra-red light, and temperatures of land, sea and cloud surfaces from rather simple radiometric measurements. The latest satellites also carry sophisticated spectrometers and radiometers to determine the vertical distribution of temperature and humidity throughout the whole depth of the atmosphere and so provide, for the first time, quantitative global data of the kind required for numerical weather prediction.

This paper will describe the requirement for global atmospheric measurements, and how these are being obtained and are likely to be obtained in the future by satellites carrying radiometric sensors and interrogation systems. It is probable that the global weather-observing and communication systems will become largely based on satellite technology during the next 10-20 years.

The requirement for global observations of the atmosphere. Each day about 8000 land stations and 4000 merchant ships make regular observations of the weather as experienced at the earth's surface. Conditions in the upper air are recorded at only a few hundred stations which send up balloon-

* Revised version of a paper with the same title originally published in *Measurement and Control*, London, 6, 1973, pp. 441-451.

borne instruments called radiosondes. The instruments record the air temperature, pressure and humidity as they ascend (and later descend attached to a parachute) and transmit their readings to the ground station or weather ship in the form of coded radio signals. The balloon also carries a reflector that permits its path to be tracked by radar and hence the winds to be measured up to heights of 30 km (100 000 ft) or more. There are more than 600 radiosonde stations in the northern hemisphere which make soundings every 6 or 12 hours, the density of the network being adequate over Europe and North America but too sparse elsewhere, especially over the oceans and the tropical regions. In fact, it is becoming increasingly difficult to maintain the network of ocean weather ships in the North Atlantic. In the southern hemisphere, which is largely occupied by ocean, there are fewer than 100 radiosonde stations altogether. In other words, the atmosphere over at least half the earth is not observed adequately to permit meteorologists to describe and forecast the evolution of even the major weather systems over the entire globe.

Nevertheless, recent research encourages the belief that, given adequate observations and computing facilities, it should be possible within the next few years to produce reliable forecasts of the main weather patterns for 5–7 days ahead and a useful indication of general trends over periods of perhaps 2–3 weeks. Forecasts on these time-scales will require very complex physico-mathematical models of the atmosphere, computers many times more powerful than existing machines, and adequate observations covering at least a hemisphere and perhaps the whole globe.

Additional observations will therefore be needed, especially from the oceanic and tropical areas and the southern hemisphere, and also faster and more reliable methods of communication for the transmission and exchange of these data, together with much more powerful computers than exist at present. The main objective of the World Weather Watch (WWW) is to obtain just these facilities. Plans for the first four-year period (1969–73) called for the establishment of a minimal global network of observations by creating about 40 new fixed radiosonde stations and providing similar facilities on 100 moving ships, and for installing a high-speed global-communication circuit linking the major meteorological centres, which will be equipped with powerful computers for processing the observational data and producing numerical forecasts. However, it is clear that an adequate global system cannot be produced at reasonable cost by simply expanding the current operational facilities, and that the World Weather Watch will ultimately depend largely on satellites for surveillance and remote sensing of the atmosphere, for the location and interrogation of instrumented balloons, ocean buoys and unmanned land stations, and for world-wide communications.

At this stage it is not possible to specify precisely the minimum and optimum standards for the coverage, spatial resolution, frequency and accuracy of the observations. This will be one of the main tasks of the Global Atmospheric Research Programme (GARP), the research component of WWW, which proposes to undertake intensive observations of the global atmosphere over a period of one year in 1978 with a view to determining the stability and limits of predictability of atmospheric behaviour, and the minimum observational and other facilities that will be necessary for the fully operational phases of WWW. GARP also plans to investigate the evolution of the mesoscale tropical weather systems and their role in transporting heat and water vapour into the

global circulation, and also the exchange of heat, momentum and water vapour between the oceans and the overlying atmosphere (see Mason¹).

As far as can be judged at present, it seems likely that, in order to forecast the large-scale dynamical features of the atmosphere that will determine the essential character of the weather everywhere for a week ahead, vertical soundings of temperature, pressure and wind up to heights of 30 km and of humidity up to 10 km will be required once, perhaps twice, daily at an average horizontal spacing of 500 km over the entire globe together with a similar density of the basic surface parameters including sea surface temperature. In terms of present facilities, this would imply an impossible requirement for about 1500 additional upper-air stations, mainly over the oceans, and so adequate global coverage will be achieved only by satellite techniques. Meanwhile, 5–7-day forecasts for at least the middle latitudes of the northern hemisphere might be possible if the present network of upper-air stations could be reinforced over the oceans, particularly at low latitudes, to give an average spacing there of 1000 km. Northern-hemisphere forecasts for 10–20 days will probably require, in addition, a similar density of observations from the southern hemisphere. Regarding the required accuracy of the observations, air temperatures to within 1 degC, atmospheric pressures to within 0.3 per cent (3 mb at the surface), winds to within 1–2 m/s, vapour pressures to within 10 per cent, and sea surface temperatures to within 1 degC may prove adequate, but all these assumptions will need to be tested, first in long-term numerical simulation experiments on the computer and ultimately in predictions using real initial data.

Satellites can provide efficient and economic global observations of meteorological parameters by measuring the intensity, polarization, and angular and spectral variation of radiation emitted and reflected by the earth and the atmosphere. In polar orbit they have the great advantage of being able to survey a large area of the atmosphere at any one instant and to cover the whole globe every 24 hours. In geostationary orbit they can observe a particular area, in fact about one-quarter of the earth, continuously. Despite the distance of satellites from the earth, the difficulties arise not so much in producing instruments that will measure the received electromagnetic radiation with the desired accuracy, resolution and coverage, but rather in discovering and exploiting physical relationships that uniquely relate the measured quantities to the desired meteorological parameters. As will be seen later, it is one thing to measure the spectral distribution of radiation received by the satellite from the underlying atmosphere, and quite another to deduce from these measurements the vertical distribution of atmospheric temperature or humidity with the accuracy required for use in numerical forecasting.

Cloud photography and mapping of the earth's surface. Ever since the first remarkable pictures were transmitted by the TIROS I satellite in 1960, the meteorologist has received an almost continuous flow of excellent photographs from a succession of American satellites. Since early in 1966 the introduction of the automatic-picture-transmission (APT) facility has made these pictures available in real-time to any country that can make, or buy for the equivalent of a few thousand pounds, the necessary receiving and reproduction equipment. More than 60 countries are now so equipped, and the photographs showing the cloud formations, and the distribution of snow on the ground and ice on the sea, are proving a most valuable aid in weather forecasting.

Excellent pictures covering the eastern half of the North Atlantic, western Europe and the Mediterranean are received daily at Bracknell. They show very clearly the organization and structure of cloud systems ranging from large cyclonic vortices 1000 km across to individual shower clouds only 1 km in diameter. Comparison of such photographs and the weather charts has, on many occasions, led to an improved analysis and forecast. Detailed analysis and interpretation of such pictures has provided valuable information on the location of such mesoscale features as hurricanes, thunderstorms, squall lines, jet streams, mountain waves and regions of strong wind shear, often from oceanic and other remote areas where the observing networks are too sparse to make their detection likely by conventional methods. The distribution of sea ice and land areas covered by ice and snow are also clearly shown.

The first television pictures were taken with a 500-line vidicon system which was soon replaced by a more advanced system having three identical cameras at 35° to each other to give overlapping views and so provide contiguous coverage of the globe. The system provides about 1000 pictures each day for storage and transmission in batches of 200 to ground stations. Each camera has a vidicon tube scanned by an 800-line raster of 800 points, the resolution of objects on the ground at the sub-satellite point being about 1 km. In order to cope with the variable illumination of the earth and cloud surfaces, the cameras are fitted with a variable iris-type stop operated by the shaft that carries the solar paddles and whose angular position is related to the solar zenith angles at the surface. The aperture is wide open over the Poles and smallest when the satellite crosses the subsolar point. Calibration of the picture intensity is provided by a uniformly illuminated wedge in the field of view of each camera, so that a stripe ranging from black to white through all shades of grey appears at the side of each photograph.

In the currentITOS (NOAA) satellites, vidicon systems have been replaced by scanning radiometers that produce both visible and infra-red images to give both day and night coverage of the earth. The pictures are built up line by line by scanning the field of view from horizon to horizon, using a mirror rotating uniformly at such a rate that the satellite advances along its orbital path just enough between each scan to provide contiguous cover at the ground. The radiation collected by the mirror is focused by a Cassegrain telescope on to a dichroic beam-splitter, the visible image then falling on a silicon photo-electric detector and the infra-red radiation on a thermistor bolometer. The ground resolution at the sub-satellite point is 4 km in the visible and 8 km in the infra-red.

TheITOS D (NOAA 2) satellite, launched in 1972, carries an additional scanning radiometer with a cooled Cd-Hg-Te infra-red detector that produces very high-quality pictures (see Plate III), with a resolution of about 0.9 km in both visible and infra-red channels.

A geosynchronous satellite, placed in equatorial orbit at an altitude of 36 000 km, rotates in synchronism with the earth and so remains stationary over a particular point on the Equator and thus allows a particular area to be observed continuously. The United States Advanced Technology Satellites (ATS), the first two of which were launched in December 1966 and November 1967 and are still operating, carry a camera (in effect a 5-inch telescope and photomultiplier) which, in scanning laterally while the satellite spins about its axis aligned parallel to the earth's axis, views a wide strip of the earth every

20 minutes. It therefore provides a time-lapse record of the movement and development of cloud systems over nearly one-quarter of the globe. The instantaneous field of view of the telescope is equivalent to 4-km resolution at the surface.

At present one such satellite is poised over the equatorial Pacific and the other over the Amazon but they can be moved if required. Plate I shows a picture taken by the latter satellite which views the whole of North and South America, western Africa and most of the Atlantic Ocean.

The first geostationary satellite designed specifically for meteorology, the United States Synchronous Meteorological Satellite (sms), launched early in 1974, carries a 16-inch Cassegrain telescope with scanning mirror. Eight photomultiplier detectors in the focal plane of the telescope provide visible images with 1-km resolution, and two Cd-Hg-Te detectors produce infra-red images with 8-km resolution. A rather similar satellite is being developed by the European Space Agency for launching at the end of 1976 and will be one of an international set of five vehicles built by the United States (two), Europe, U.S.S.R. and Japan to provide global coverage during the First Global Observing Experiment of the Global Atmospheric Research Programme in 1978.

Measurement of surface temperatures. In addition to providing images, the radiometers can determine the temperatures of land, sea and cloud surfaces by measuring the infra-red radiation emitted by them in the 10.5–12.5- μ m atmospheric window.

The intensity I of the radiation received by the satellite detector when there is no intervening cloud consists of two components, that originating from the surface of temperature T , and that from the atmosphere with mean temperature of T_a .

Thus:

$$I_v = \epsilon \tau B_v(T) + (1 - \tau) B_v(T_a) \quad \dots (1)$$

where $B_v(T)$ and $B_v(T_a)$ are Planck functions appropriate to the frequency ν and temperatures T and T_a respectively. In order to determine T it is necessary to know the emissivity ϵ of the surface and the transparency τ of the intervening atmosphere. The emissivity of ocean and vegetation-covered surfaces is nearly unity but that of bare rock and soil may be as low as 0.5. Some absorption is caused in the 'window' by water vapour and CO_2 and, being strongly temperature-dependent, is not easy to correct for. In a warm, humid atmosphere the correction may be as high as 5 degC, so the distribution of atmospheric temperature and water vapour needs to be known rather accurately if these corrections are to be properly made. Additional absorption may be caused by dust and other aerosols, especially over land.

The very high-resolution scanning radiometer (VHRR) on rros D is able to discriminate equivalent black-body temperature differences of 0.5 K for a 300-K scene, but the degradation that follows transmission and data-processing allows the temperature of land surfaces to be determined to within about 2 K and of ocean surfaces to within 1–1½ K.

Measurements from polar orbiting satellites have been compiled to produce maps of cloud-summit temperatures (see Figure 1) and of temperature anomalies in the oceans, but continuous tracking of the latter is often prevented by intervening cloud. In the case of non-raining clouds at least, interference may

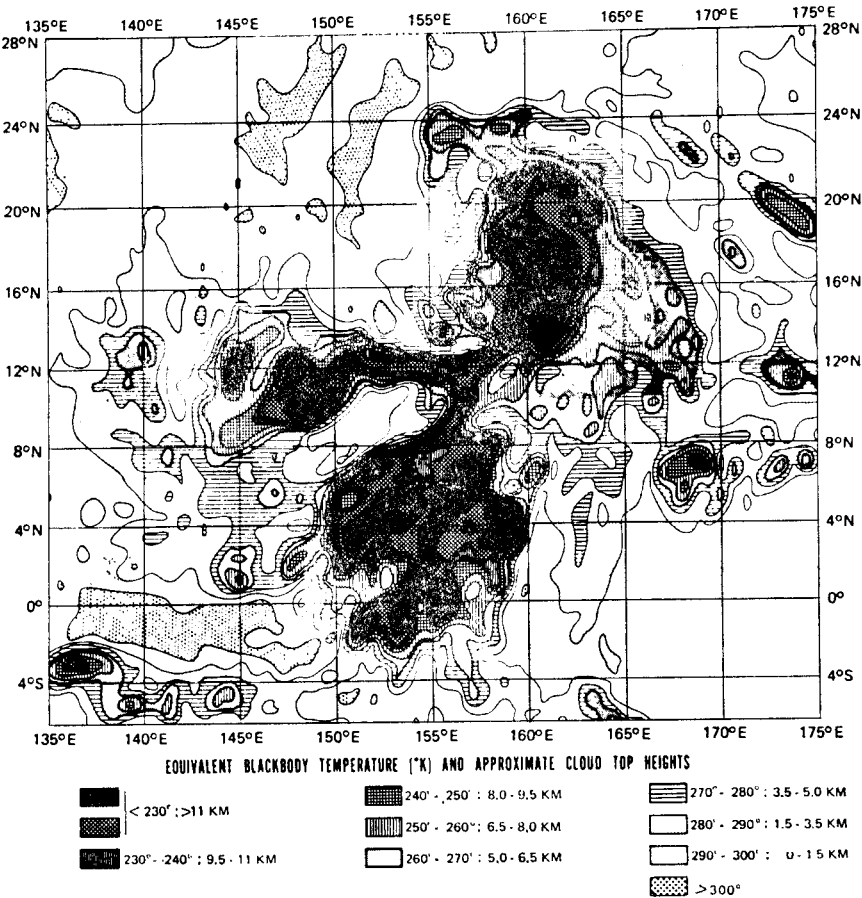


FIGURE 1—THE TEMPERATURE OF THE CLOUD TOPS ASSOCIATED WITH TYPHOON 'MARIE' AND A TROPICAL DEPRESSION, AS DEDUCED FROM A HIGH-RESOLUTION INFRARED RADIOMETER ON NIMBUS 2 ON 31 OCTOBER 1966
(From NASA, Nimbus 4 User's Guide)

be largely overcome by using microwaves (e.g. in the 1.6-cm window), but many natural surfaces are not black for microwaves, and their emissivities would have to be determined.

Measurements of radiative flux. The incoming solar radiation, the primary source of energy for driving the atmospheric circulation, can be measured accurately only outside the atmosphere by rocket or satellite. Measurements of the solar flux can be made either with high-resolution spectrometers on sun-stabilized satellites, or with wider-band radiometers on earth-oriented satellites by scanning the sun for, say, 20 minutes during each orbit. At present, measurements of the solar constant have probable errors of about 1 per cent, but the intensity of the ultra-violet portion is much more variable and less well documented. The outgoing solar radiation reflected back to space by the atmosphere and the earth has been measured on American and Russian

satellites, but there are difficulties in estimating the total hemispheric flux from narrow-beam measurements and in allowing for angular and spectral variations.

The outward flux of long-wave terrestrial radiation in the 4–30- μm band was one of the first parameters to be measured from a satellite. Existing broadband radiometers can measure the intensity of radiation received from a given direction with an accuracy of 1 per cent, and with angular resolution of better than 1° . Since the filters and detectors used in radiometers do not permit uniform response over the entire spectral range, and because each area on earth is viewed through a narrow aperture, it is again necessary to use analytical and empirical models to relate the measurements to the total emitted flux over the hemisphere.

Nevertheless, sufficiently accurate measurements of both incoming and outgoing radiation have been made to permit the derivation of useful global maps of the net amount of energy available to the earth and atmosphere and to give some indication of the day-to-day changes in the heat balance of the system. It appears that over a 4–5-year period the net-radiation budget of the entire earth and of each hemisphere separately is in radiative balance to within the limits of experimental error (i.e. better than 1 per cent). Each hemisphere has nearly the same planetary albedo — about 30 per cent — which demonstrates the dominant influence of clouds on the energy exchange with space, since the surface features of the two hemispheres are quite different.

Although the cloud pictures and radiation data from satellites currently provide a great deal of valuable information, it is mainly only qualitative in character and very difficult to incorporate directly into numerical weather-prediction models which require data on atmospheric temperature, pressure, composition and winds. This information can be obtained by remote sensing of the atmosphere from satellites.

Remote sensing of atmospheric temperatures

(a) *Theory of the method.* In contrast to the simple radiometers required for the determination of total fluxes and surface temperatures, a number of very sophisticated and ingenious spectrometers and radiometers are being developed to obtain the vertical distribution of atmospheric temperature from measurements of the spectral distribution of radiation received from constant constituents such as carbon dioxide or molecular oxygen.

The radiation emitted by a layer of uniformly mixed gas in local thermodynamic equilibrium is directly dependent on its temperature. But the intensity of the infra-red radiation reaching a satellite from, say, the carbon dioxide distributed throughout the depth of the atmosphere, even through a window in which absorption by other constituents is negligible, will also be affected by absorption within the gas itself.

Thus relatively little radiation is received from the comparatively small mass of emitting gas in the uppermost layers, and comparatively little also from the lowest layers whose emission is strongly attenuated in traversing the whole depth of the atmosphere. The received radiation therefore comes mainly from the intermediate levels and is weighted according to height (or total pressure), as indicated by a function of the form shown in Figure 2.

The intensity of radiation emitted in a vertical direction from a horizontal slice of the gas of thickness dz in a narrow band of central frequency ν is

$k_\nu dz \cdot B_\nu(T)$, where k_ν is the absorption coefficient. Of this, only a fraction τ will reach the top of the atmosphere where τ is the transmittance.

The total intensity of the radiation at the top of the atmosphere due to all such slices is then:

$$I_\nu = \int_0^\infty B_\nu(T) k_\nu \tau_\nu dz$$

but

$$\tau_\nu = \exp(-\int k_\nu dz)$$

so that

$$d\tau_\nu = -k_\nu dz \cdot \exp(-\int k_\nu dz)$$

and

$$\begin{aligned} I_\nu &= \int B_\nu(T) d\tau_\nu = \int B_\nu(T) \frac{d\tau}{dy} dy \\ &= \int B_\nu(T) \frac{d\tau}{d(\ln p)} d(\ln p) \quad \dots (2) \end{aligned}$$

where the weighting function $d\tau/dy$ may be more conveniently expressed in terms of the variable $y = -\ln p$, where p is the total pressure, instead of the height z because this is more nearly independent of temperature. The weighting function for a single frequency ν chosen in the wing of a collision-broadened spectral line (collision broadening is dominant in the lowest 50 km of the atmosphere) is shown in curve A of Figure 2. The value of the pressure p_0 at which the weighting function reaches a maximum depends on the particular wavelength chosen but the half-width of the curve in units of $\ln p$ is independent of wavelength. Since for an isothermal atmosphere, $\ln p \propto z$, the half-width in height units is approximately constant and equal to 10 km.

In practice many of the radiometers designed for temperature sounding in the 15- μm CO_2 band possess a band width of about 5 cm^{-1} and so receive radiation from the wings of several lines in the band. Consequently they do not have the ideal monochromatic response represented by curve A but rather broader weighting functions such as curve B in Figure 2, which give somewhat poorer height resolution.

So far attention has been restricted to a single frequency or a narrow spectral interval for which the altitude of the peak of the weighting function depends on the absorption coefficient at the particular frequency and on the concentration of the emitting gas. Because in any absorption band the absorption coefficient varies rapidly with frequency, different frequencies possess different weighting functions peaking at different altitudes as shown in Figure 3. Thus a set of measurements of the radiation received in several narrow frequency intervals, chosen so that the corresponding intensities each originate from substantially different levels in the atmosphere, provide information on the vertical distribution of temperature.

The weighting functions may be calculated from the optical characteristics of the radiometer and detailed spectral information on the positions, intensities, widths and shapes of the spectral lines emitted by the gas. Alternatively, they may be determined in the laboratory by measuring with the actual satellite radiometer the transmission through a synthetic atmosphere.

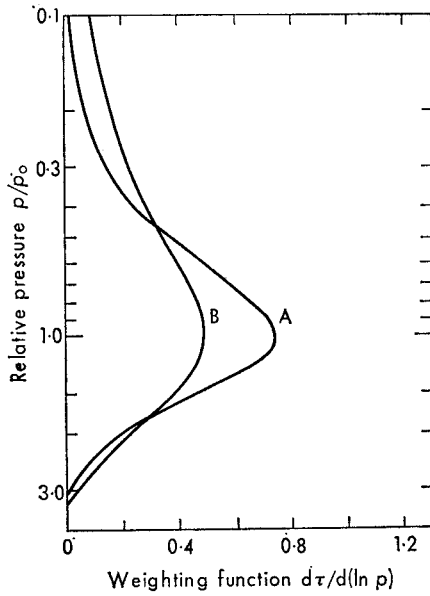


FIGURE 2—WEIGHTING FUNCTIONS FOR A MONOCHROMATIC FREQUENCY IN THE WING OF A COLLISION-BROADENED LINE (A), AND RADIATION RECEIVED FROM THE WINGS OF SEVERAL LINES IN THE CO_2 BAND (B)

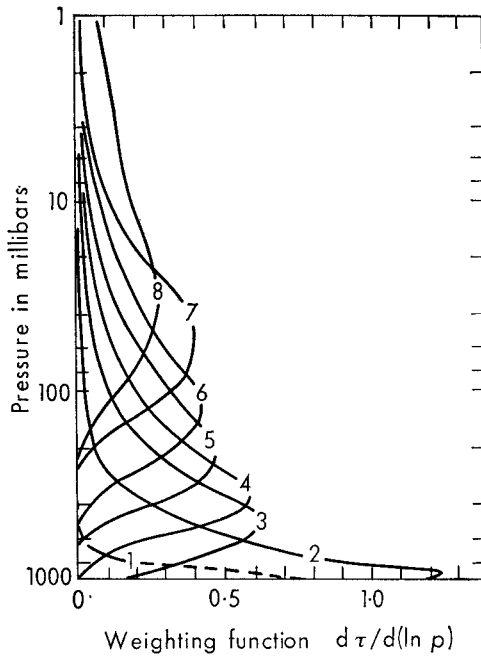


FIGURE 3—WEIGHTING FUNCTIONS FOR THE SIRS INSTRUMENT ON NIMBUS 3

The important quantities which determine the quality of a set of measurements from a vertical-sounding radiometer are the vertical resolutions and the accuracy of measurement. To be useful, measurements of the mean temperature over layers about 200 mb thick need to be made with a probable error of less than 1 K, which means that in the 15- μ m CO₂ band radiances have to be measured to better than 1 per cent. The radiance received from a clear atmosphere at a particular frequency represents the appropriate black-body function multiplied by a weighting function of the type shown in Figure 2. The weighting function, which is quite broad, will overlap with similar functions appropriate to other frequencies so that the retrieval of the temperature profile from a set of measured radiances is not a simple matter. Because of the rather coarse height resolution, the overlapping of the weighting functions and the noise in the observations, this retrieval cannot be done exactly and it is important to know the accuracy of a given result.

Although it is possible, in principle, to retrieve the temperature profile from the radiance measurements by, in effect, inversion of the radiative-transfer equations, in practice it has been found more profitable to include statistical information available from conventional (radiosonde) temperature soundings. Thus, in reducing the data from the SIRS instrument on the NIMBUS 3 satellite, the measured radiances are related to atmospheric temperatures through statistical regression equations derived from a large sample of radiosonde soundings, determined for five latitude belts between the North Pole and the South Pole and updated every few days. Equations are derived both for the temperature and for the geopotential height of 13 standard pressure levels between the surface and 10 mb (30 km). Intermediate levels are computed from the hydrostatic equation so that each profile is determined by 25 levels. The radiances are measured over a field of view of 225 km square so that the temperatures represent an average over this area. The eight channels are sampled simultaneously at 8-second intervals during which the spacecraft travels about 50 km. Global coverage is achieved twice each day — at noon and midnight local time. Day-time and night-time observations are obtained with equal precision.

The presence of clouds in the field of view enormously complicates the retrieval of temperature information from the lower atmosphere. With heavy cloud cover, radiometer measurements can be made only above the cloud tops, and the sounding from the cloud top to the earth's surface must be interpolated between satellite-derived temperatures and a known surface air temperature. With partial cloud cover, the radiance measurements are affected by the cloud amount and the heights and constitution of the cloud layers whose optical properties are not well known. In this case, a statistical technique is used to derive a simulated clear-air sounding that SIRS would have obtained had the clouds not been present in the field of view. Data from the more opaque SIRS channels (which measure radiance mainly from higher cloud-free levels) are used with the surface air temperature to obtain a first approximation to the clear-air sounding below the clouds. Data from the remaining channels are compared with the radiance values implied by this first approximation. The departures are used, with a few iterative steps, to improve the approximation to the clear-air sounding in the lower levels, and to produce an estimate of height and amount of one or two cloud layers which could account for the observed departures. This method has been extended to obtain results from

the ITPR radiometer on NIMBUS 5, whose much-improved resolution (about 50 km square) allows a large number of neighbouring observations to be made over an area where the temperature profile and cloud height may be assumed to remain constant but where the cloud amount may well vary. The cloud amount may be eliminated from such observations to produce good determinations of temperature profile and cloud height.

An entirely different approach to the cloud problem developed by Rodgers⁵ uses the known statistical properties of the atmosphere to derive the most probable temperature profile, cloud height and amount consistent with the set of radiance observations. A different set of statistics has to be used for each season.

Figure 4 shows the historic first temperature sounding derived from satellite measurements and, for comparison, the radiosonde sounding taken from Kingston, Jamaica, about 400 km to the north-west and 4 hours earlier in time. Close agreement between the two is evident. The main difference lies in the middle troposphere, where the SIRS sounding is warmer by 2 or 3 degC. Systematic errors of this type are rather typical and arise mainly from inadequate knowledge of the transmittance functions of carbon dioxide and water vapour. In practice, they may be reduced by using past SIRS observations coincident

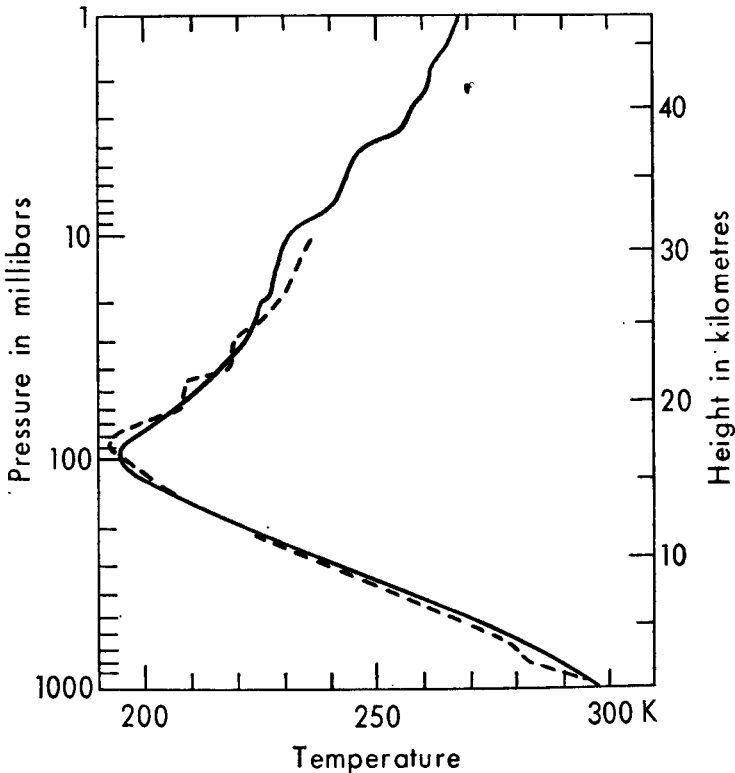


FIGURE 4—COMPARISON BETWEEN SIRS RADIOMETER SOUNDING AND RADIOSONDE ASCENT AT KINGSTON, JAMAICA, ON 14 APRIL 1969

— SIRS, 16°N 73°W, 1612 GMT, in clear-sky conditions.
 - - - Kingston radiosonde, 1200 GMT.

in space and time with radiosonde data as observed *radiances* in deriving the statistical regression equations, thus avoiding the need to specify the carbon dioxide transmittances explicitly. When these rather empirical methods are used to deduce the temperature profiles, the discrepancies between the SIRS-derived and radiosonde-observed temperatures are between 1.5 and 2 degC for 70 per cent of soundings in the northern hemisphere. Less than 2 per cent of the discrepancies exceed 6 degC, the largest errors occurring in the lower troposphere owing to the influence of clouds. The data for the southern hemisphere are not so good because there are so few radiosonde soundings on which to base the regression equations; here satisfactory methods of inverting the radiative transfer equations are not yet available.

(b) *Instruments.* A radiometer for temperature sounding consists essentially of an optical system for defining the field of view and gathering the energy, a monochromator to select the narrow spectral intervals, and a detector. About six independent spectral channels are required to cover the lowest 50 km of a clear atmosphere but, because of the need to identify surface characteristics, clouds, and water-vapour distribution as well, about twice this number of channels is required in practice. Several techniques have been developed for selecting the frequency intervals and for measuring the radiation received.

The Satellite Infra-red Spectrometer (SIRS), launched in April 1969 on NIMBUS 3, was the first temperature-sounding experiment capable of providing a vertical profile. Eight channels, 5 cm^{-1} wide in the $15\text{-}\mu\text{m}$ band of CO_2 , were chosen to cover the atmosphere from the surface to about 35 km. The instrument is an Ebert spectrometer using a fixed grating with slits in the image plane and a rotating-mirror chopper. This is a highly reflecting rotating blade which alternately views the radiations received from the underlying atmosphere and a reflected image of space to produce an a.c. signal which is detected by a thermistor bolometer. Radiometric and wavelength calibrations are made by using an object mirror which allows the instrument to view an internal black-body at the temperature of liquid nitrogen with and without a calibration filter. The field of view is 12° , which gives a resolution of about 200 km at the earth's surface. A further SIRS instrument was launched on NIMBUS 4 satellite in April 1970 but worked for only a limited period.

NIMBUS 3 also carried an Infra-red Interferometer Spectrometer (IRIS), which was essentially a Michelson interferometer scanning the entire spectrum from 5 to $25\text{ }\mu\text{m}$ with a resolution of about 5 cm^{-1} . An improved version on NIMBUS 4 has a still higher resolution of 2.8 cm^{-1} . The spectra provide information on the atmosphere's temperature profile in the $15\text{-}\mu\text{m}$ CO_2 band and also on the distributions of water vapour and ozone. The instrument consists essentially of a multilayered beam-splitter, a moving mirror which advances evenly and without tilt, and a thermistor bolometer detector. A second complete interferometer is incorporated for reference purposes and this uses a discharge lamp as source and a photovoltaic cell as detector. The instrument views the earth via a gold-plated mirror which tilts to view space or an internal black-body when calibration is required.

A simpler instrument, called a Selective Chopper Radiometer (SCR), developed at Oxford and Reading Universities, first flew on the NIMBUS 4 satellite. It employs narrow-band (3.5 cm^{-1}) interference filters to select six channels in the $15\text{-}\mu\text{m}$ CO_2 band and absorption cells containing CO_2 to filter and select further the radiation. For the four channels observing the lower

levels of the atmosphere below 30 km, the received radiation passes through the absorbing paths of CO₂, and so these channels are no longer sensitive to radiation originating near the centres of the absorption lines and, therefore, from regions of high altitude. The weighting functions for the lower levels are thereby sharpened, to give increased resolution while allowing the collection of sufficient energy for measurements of adequate accuracy to be made. Weighting functions peaked at high levels are obtained by optically chopping the incoming radiation between two cells, one containing CO₂, the other being empty. An alternating signal is obtained which is dependent only on the radiation absorbed by the CO₂ in the absorbing cell; that is, the system is responsive to just those frequencies absorbed by the CO₂. The resulting weighting functions can be made to peak well in the upper stratosphere. Figure 5 shows the optical design of the SCR on NIMBUS 4. The view through each cell is switched between earth and space by a vibrating mirror, so that an a.c. signal appears at the detector and is amplified by an electronic system tuned to the chopper frequency. The detector is a thermistor bolometer, and calibration is achieved by using an object mirror that views the earth, space

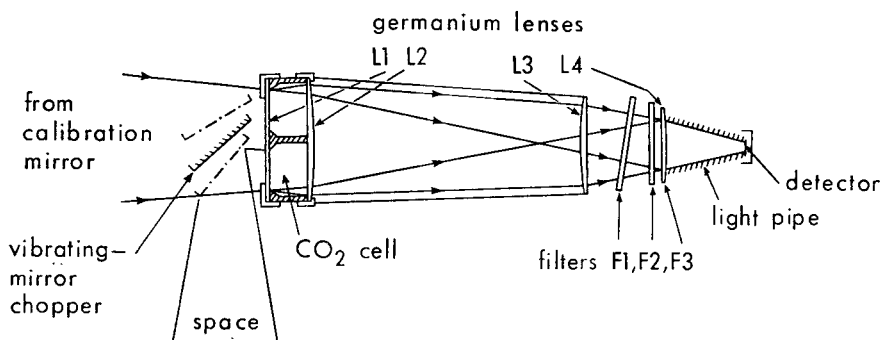


FIGURE 5—OPTICAL SYSTEM OF THE SELECTIVE CHOPPER RADIOMETER (SCR) ON NIMBUS 4

and a black-body of known temperature in turn. With this instrument good temperature retrievals are possible up to 50-km altitude, an example being shown in Figure 6.

The NIMBUS 5 satellite, launched in December 1972, carries a more elaborate SCR with 16 channels — eight CO₂ channels, a channel at 19.2 μm for sounding water vapour, four channels for detecting cirrus clouds, which greatly complicate temperature retrievals, and three window channels. Pyroelectric detectors, having a much better performance than thermistor bolometers, allow the field of view to be reduced to only $1\frac{1}{2}^\circ$, which gives a horizontal field of only 25 km at the earth's surface. This considerably increases the probability of looking through holes in the cloud and of any cloud cover being uniform within the field.

NIMBUS 5 also carries an American-built Infra-red Temperature Profile Radiometer (ITPR) with seven channels selected by filters. Each channel has a separate optical system, four being in the 15- μm CO₂ band, one at 20 μm for water-vapour determination, and two window channels at 11 μm and 3.8 μm respectively. Because of the narrow field of view ($1\frac{1}{2}^\circ$), successive measurements can be made while scanning over a grid containing about 140 elements in a

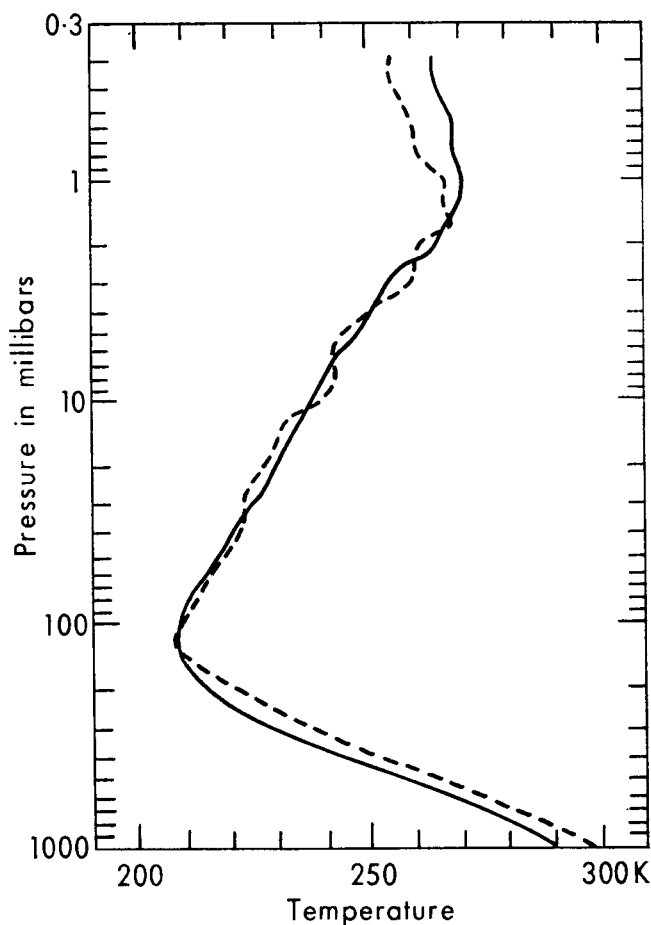


FIGURE 6—COMPARISON BETWEEN TEMPERATURE PROFILES ON 27 AUGUST 1970, RETRIEVED FROM SCR RADIOMETER ON NIMBUS 4 AND DEDUCED FROM RADIO-SONDE AND ROCKETSONDE ASCENTS FROM WALLOPS ISLAND

— SCR on NIMBUS 4.
 - - - Wallops Island radiosonde and rocketsonde.
 (From Barnett *et alii*³)

total time of 64 seconds. On the assumption that the temperature structure is uniform over the area of such a grid while the cloud structure may vary, and by using observations in the two window regions, a retrieval method can be devised that adequately eliminates the cloud structure from consideration.

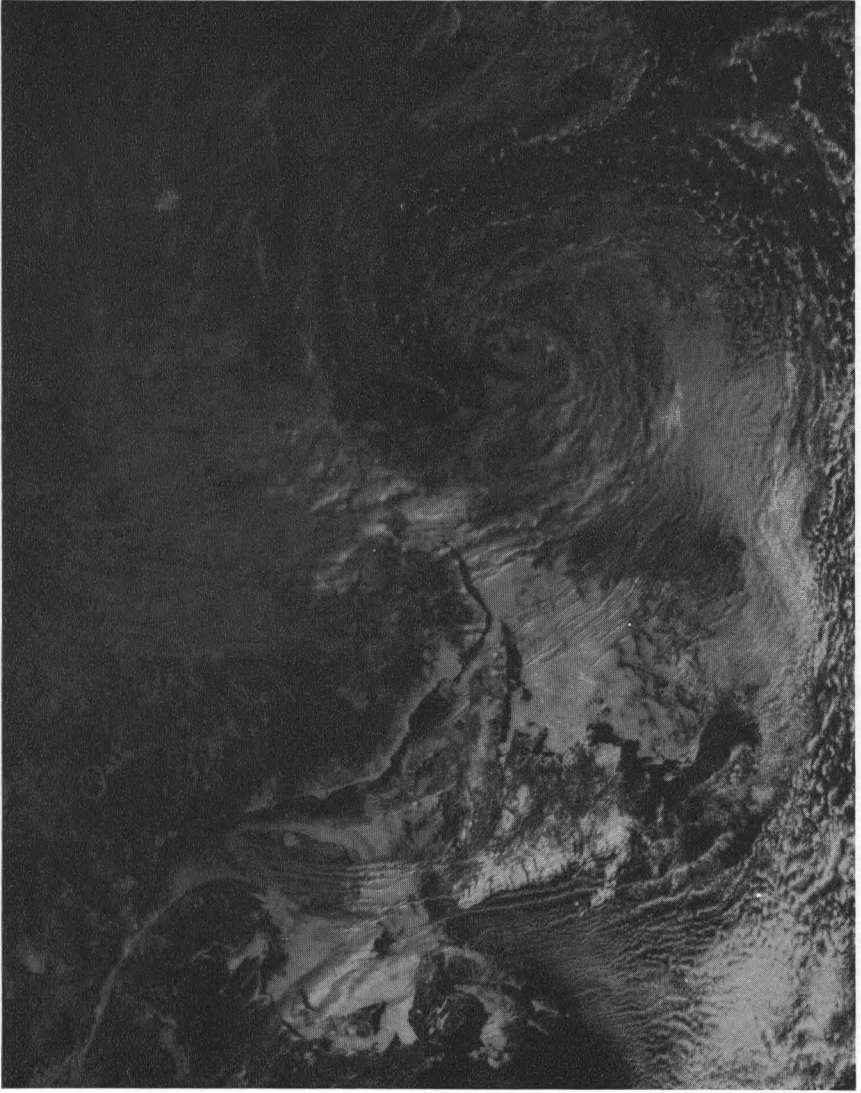
The Pressure Modulator Radiometer (PMR). If with a selective chopper radiometer it is required to select radiation from close to the centres of the lines, i.e. from high altitudes, optical balancing of the double-beam system becomes very difficult. A technique to overcome this employs a cell of CO_2 gas in which the pressure is varied cyclically by a piston. This varies the strength and width of the CO_2 absorption lines so that the radiation falling on the detector is modulated only at frequencies which lie within the absorption



Photograph by courtesy of the United States National Aeronautics and Space Administration

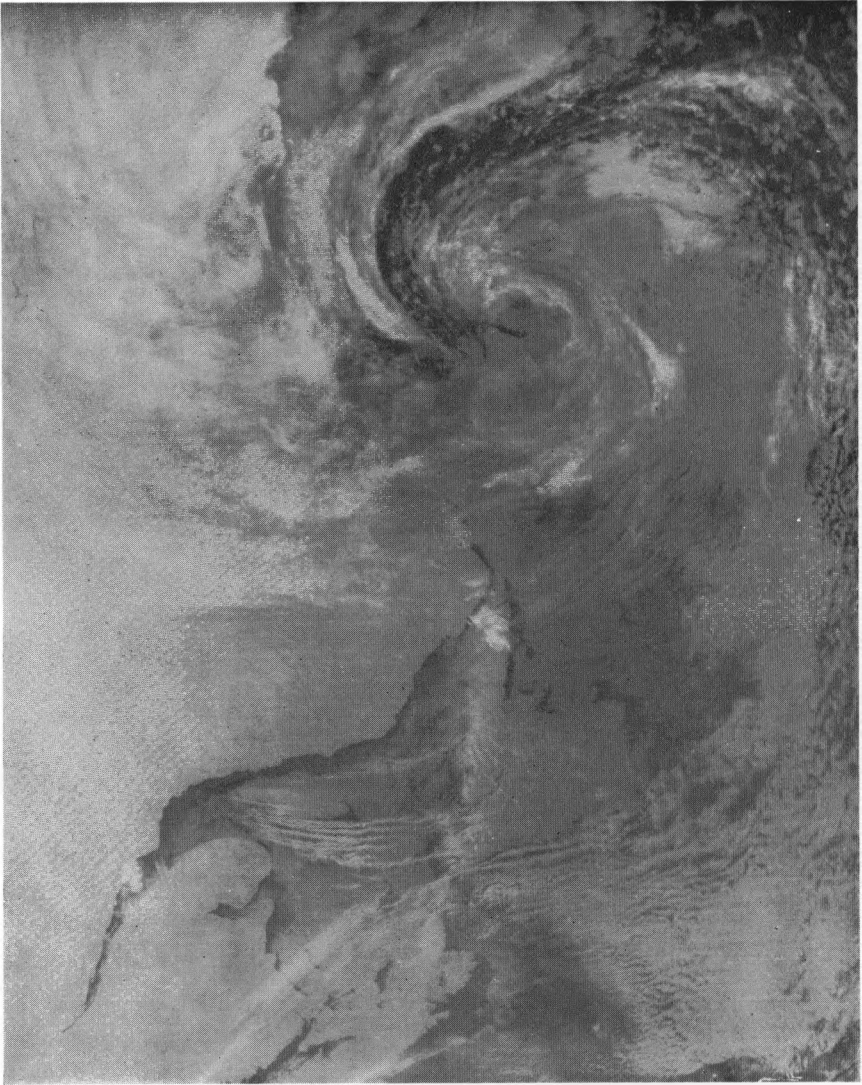
PLATE I—PICTURE TRANSMITTED (ACTUALLY IN COLOUR) FROM THE UNITED STATES ATS-3 GEOSYNCHRONOUS SATELLITE OVER THE AMAZON, SHOWING THE WHOLE OF SOUTH AMERICA, NORTH AMERICA AND WESTERN NORTH AFRICA

Prominent among the many cloud systems are the spiral pattern associated with a small depression off the coast of Morocco, a long line of convective clouds stretching east-west over the southern parts of the North Atlantic and a cold frontal system over Uruguay and north Argentina.



Photograph by courtesy of the United States National Oceanographic and Atmospheric Agency

PLATE II—PHOTOGRAPH TAKEN FROM THE VERY HIGH RESOLUTION RADIOMETER (VHRR) ON THE NOAA 2 SATELLITE SHOWING A DEPRESSION CENTRED SOUTH OF GREENLAND, AND ICE IN THE GULF OF ST LAWRENCE IN VISIBLE WAVELENGTHS



Photograph by courtesy of the United States National Oceanographic and Atmospheric Agency

PLATE III—PHOTOGRAPH TAKEN FROM THE VERY HIGH RESOLUTION RADIOMETER (VHRR) ON THE NOAA 2 SATELLITE SHOWING A DEPRESSION CENTRED SOUTH OF GREENLAND, AND ICE IN THE GULF OF ST LAWRENCE IN THE INFRA-RED

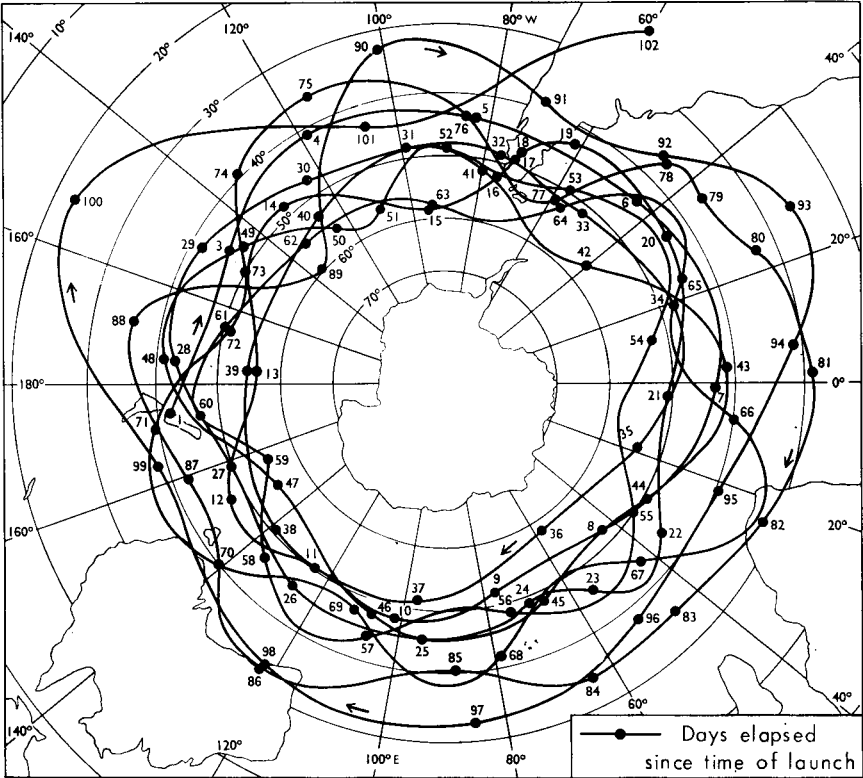


PLATE IV—TRAJECTORY OF A BALLOON RELEASED FROM CHRISTCHURCH, NEW ZEALAND, WHICH MADE EIGHT CIRCUITS AT 200 mb ($\approx 40\,000$ ft) DURING 102 DAYS

lines of the gas. The weighting function for the modulated component of radiation passing through such a cell has its peak at a pressure height in the atmosphere proportional to the mean pressure of the gas in the cell, so that by using cells filled to different pressures, weighting functions peaking at different heights can be obtained. Because the wavelength selection and chopping are done by the gas itself, the PMR system is independent of changes in filters, windows and choppers which cause difficulties in other systems.

The piston, mounted on springs, oscillates at a resonant frequency of about 15 Hz with a clearance of only 0.001 in, so that leakage of gas past the piston is not a problem. The PMR is thus a simple, robust instrument and has the great advantage of being sensitive only to energy at the required frequencies while rejecting the rest. Figure 7 shows a diagram of a pressure modulator cell with its optical system. Such an instrument is being built for the NIMBUS F satellite due for launch in 1974 and the Meteorological Office plans to build several similar instruments, each having three channels with a common mirror and black-body, but separate pyroelectric detectors, for the U.S. TIROS N series of satellites that will become operational from 1977 onwards.

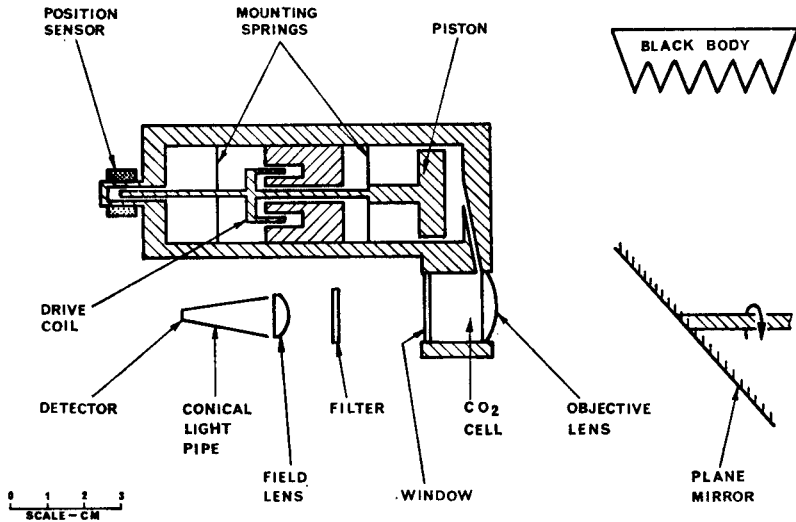


FIGURE 7—SIMPLIFIED DIAGRAM SHOWING ONE CHANNEL OF THE PRESSURE MODULATOR RADIOMETER

(From Abel *et alii*²)

Microwave radiometers. All instruments described so far observe infrared emissions from the $15\text{-}\mu\text{m}$ CO_2 band, where the presence of clouds presents a severe problem in the retrieval of tropospheric temperatures. In principle, the cloud problem can be overcome by using microwaves, since all but heavily precipitating clouds are practically transparent to radiation at these frequencies. Oxygen, which is uniformly distributed to high levels in the atmosphere, has suitably strong emission/absorption lines at about 5-mm wavelength and these may be used for temperature sounding. The NIMBUS 5 satellite carries an experimental instrument with five channels, one in a water-vapour absorption band, one in an atmospheric window, and three in the 5-mm O_2 absorption band. The last three are used to obtain temperature profiles from near the

ground up to about 20 km. The main disadvantages of the instrument are its weight and power requirements, its rather large field of view, and the fact that the emissivity of the underlying surface varies with the moisture content of the soil and the height of oceanic waves. Nevertheless, the instrument on NIMBUS 5 is working much better than expected and is producing temperature profiles comparable in quality with those obtained from the Infra-red Temperature Profile Radiometer; moreover profiles obtained by using data from both instruments are better than those obtained from each device separately.

Experience with the SIRS, SCR and ITPR instruments has demonstrated convincingly that atmospheric soundings from satellites are feasible. With further improvements in instrumentation and analysis technique (and several are already under development) it should be possible to produce a global coverage of observational data at least as accurate as that now being provided over only limited areas by conventional methods. In the stratosphere, the satellite data are probably already more reliable than radiosonde data, which are subject to large instrumental errors at these levels.

Measurement of water vapour. The simple infra-red radiometers flown on the early TIROS satellites possessed a channel in the 6.3- μm water-vapour band in order to estimate atmospheric humidity. At constant humidity, and in the absence of cloud, the optical depth of water vapour will be a function of temperature only. Consequently, at constant humidity, a roughly constant radiating temperature will be observed in the water-vapour band. Variations in radiating temperature, therefore, arise from variations in the water-vapour content of the tropospheric column. Comparison with the 8–12- μm window region allows correction for the presence of cloud, but with considerable uncertainty because of the strong variation of cloud properties with wavelength in this part of the infra-red spectrum.

More-refined measurements of water-vapour distribution have been made with the IRIS instruments on NIMBUS 3 and 4, and with the SIRS instrument on NIMBUS 4, which included six channels in the rotation band of water vapour between 20 μm and 40 μm . A water-vapour profile produced by the SIRS instrument is shown in Figure 8 and is compared with a nearby radiosonde sounding. The microwave spectrometer on NIMBUS 5 incorporates a single channel near $\lambda = 1.35$ cm to determine the total water vapour in a vertical column beneath the instrument, but because of the large and variable emissivity of the underlying land surface the method gives acceptable results only above the oceans. It should be possible to measure the low water-vapour concentrations in the stratosphere by using the pressure modulation radiometer.

The measurement of atmospheric pressure or density. Accurate determination of the vertical temperature distribution would allow the pressure (or density) profile to be calculated from the hydrostatic equation:

$$\frac{1}{p} \frac{dp}{dz} = \frac{-g}{RT}, \quad \dots (3)$$

provided that the surface pressure p_0 is known. Accurate measurements of the surface pressure on land is readily achieved by modern automatically recording aneroid barometers. The problem is much more difficult over the oceans, where it would be possible but very expensive to mount aneroid barometers on floating buoys that could be located and interrogated by satellites (see page 200). However, this may be rendered unnecessary by the recent development

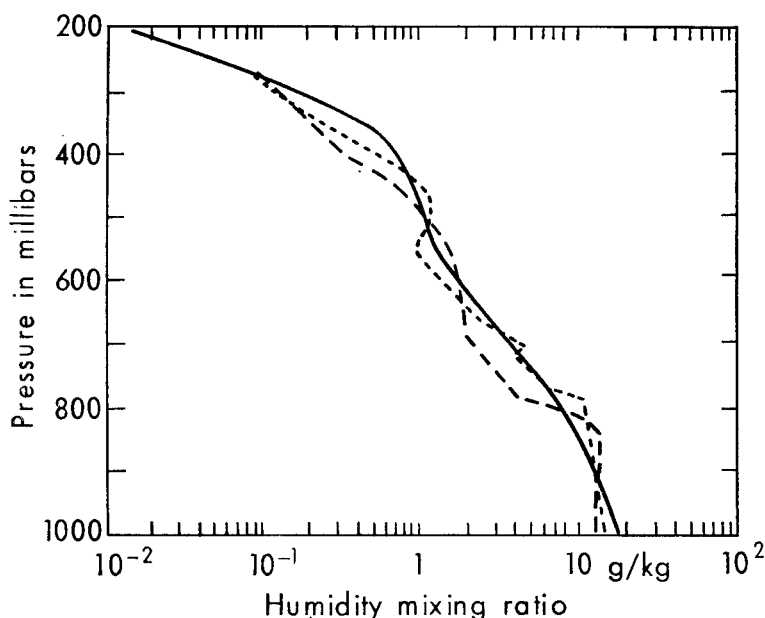


FIGURE 8—COMPARISON BETWEEN WATER-VAPOUR PROFILE RETRIEVED FROM RADIANCE OBSERVATIONS ON NIMBUS 4 (SOLID LINE) AND RADIOSONDE OBSERVATIONS MADE 3 HOURS EARLIER AND 3 HOURS LATER (DASHED LINES)
(From Smith⁴)

in the U.S.A. of a simple light-weight radar altimeter which, when mounted on a constant-level balloon (see page 198) at, say, 100 mb (≈ 16 km), can measure the height z of the balloon above the sea surface to within an accuracy of ± 3 m. Hence if the balloon carries instruments to measure the ambient pressure and temperature, the parameters p , T and z in the hydrostatic equation are known, and p_0 may be calculated. Given now the surface pressure, and T as a function of z from the infra-red spectrometer data, the pressure may be determined as a function of height z from equation (3).

Alternatively, the profile of atmospheric density could, in principle, be obtained directly from satellite measurements of the refraction of starlight, the refraction of microwaves, or the absorption of light by the molecular constituents of the atmosphere.

The satellite could make continuous measurements of the angular position of a given star, which depend on the degree of refraction which the light rays suffer in passing through the earth's atmosphere.

A series of such measurements, made between the time when the star is acquired slightly above the horizon until occultation occurs, i.e. over a period of about 30 seconds, could be used to derive a profile of refractive index (and hence air density) at a point where the rays are tangential to the earth on the assumption that the atmosphere is spherically stratified. The method has not yet been tested, but calculations suggest that it should be possible to map the profiles in the lower stratosphere and upper troposphere to within an accuracy of a few per cent. It will probably not be possible to make measurements at

lower levels, say, below 5 km, because of atmospheric extinction and occultation by cloud.

It has also been suggested (but not tried), that, since the velocity and direction of propagation of microwaves are functions of the refractive index (and hence density) of the atmosphere, precise measurement of these parameters could be used to determine atmospheric density and its variations. The technique envisages a master satellite followed by five or six slaves in low orbit around the earth. Microwaves transmitted between the master and the slaves would traverse the atmosphere at five or six different levels, and accurate measurement of their velocity and phase would continuously measure the bending and retardation of the waves averaged over the horizontal ray paths at these levels. Measurement of a 1-mb pressure change would require the system to detect a change of 1.4 m in the apparent position of the two satellites, something which could probably be achieved by Doppler measurements if the physical separation of the satellites were known with great precision. In a dry atmosphere it might be possible to derive the pressure field to within ± 1 mb in the horizontal and within ± 5 mb in the vertical, but the presence of water vapour is likely to reduce the accuracy of the method, especially at low levels.

The intensity of radiation reflected from the ocean surface on arriving at a satellite would depend on the total quantity of absorbing gas in its path, i.e. on the total pressure. This suggests that the total (surface) atmospheric pressure could be obtained by measuring the absorption of a beam from a laser on a satellite in its double path to the ocean surface and back. Two nearby frequencies would be used, one in a strong oxygen absorption line and one just outside the line. However, reflections from clouds and absorption by water vapour would probably make it difficult to achieve the required accuracy of better than 0.3 per cent.

Measurement of global winds. No really feasible method has been proposed for sensing winds simultaneously at a number of given levels in the atmosphere from a satellite. Determination of the pressure and temperature fields as described above would allow the winds to be calculated in middle and high latitudes where the winds are closely related to the pressure field through the controlling action of the Coriolis force due to the earth's rotation. This would not be possible in the tropical regions where the horizontal gradients of temperature and pressure, and the Coriolis forces, are all weak, but elsewhere it may well prove possible to derive the large-scale wind field from measurements of surface pressure and vertical temperature distribution only.

Meanwhile, American meteorologists are devoting considerable effort to the extraction of winds from the movement of clouds on the pictures transmitted on successive frames from the spin-scan cameras carried on the geostationary satellites.

Although this technique does not allow one to obtain a complete horizontal coverage of winds, or information at more than about two levels in the vertical, it is producing much useful information in data-sparse areas such as the tropics where there are very few other sources of wind data (see, for example, Plate IV). However, greatest attention has been paid to the measurement of winds by tracking inextensible, constant-volume, super-pressurized balloons that drift with the winds along surfaces of constant atmospheric density. In the United States' GHOST (Global Horizontal Sounding Technique) Project, more than

200 such balloons have been released from Christchurch, New Zealand, and tracked by the signals from a simple telemetering photoresistor device that measures the elevation of the sun. Balloons flying at 100 mb and higher are able to remain aloft for many months and make many circuits of the globe. One has flown for more than 420 days, circling the southern hemisphere more than 25 times at the 100-mb level. Balloons flying at the 200-mb level (40 000 ft) have an average life of about 100 days, Plate IV showing the trajectory followed by one such balloon in making eight circuits of the southern hemisphere over 102 days. Unfortunately balloons drifting at lower levels suffer with varying degrees of severity from the accumulation of frost, ice and snow, which limits their duration to weeks, or even a few days. If the balloon lifetime can be increased, the icing problem overcome, and an electronics package designed that will present no hazard to aircraft, this technique is likely to become an important component of World Weather Watch. Adequate global data on winds and much valuable temperature and pressure data could be supplied by keeping perhaps 6000 balloons circling the earth at altitudes between 3 and 25 km. They would be located and interrogated by a system of satellites and their data relayed to a ground-based computer for analysis.

Three alternative systems are being actively investigated. The IRLS (Interrogation, Recording and Location System) being developed by NASA, will determine the location of a balloon by measuring the propagation time of a two-way radio signal between the satellite and the platform for two positions of the satellite in the same orbit. These two range measurements and the exact time of the measurement in relation to the known geometry of the orbit are all that is required to establish the position of the balloon. A similar determination made during the next orbit, about 100 minutes later, will give the balloon's displacement and hence the average wind over this time interval. Design studies suggest that the total error in range measurement may not exceed 0.5 km, in which case it should be possible to locate a balloon to within ± 3 km and to give average winds to within ± 1 m/s.

The EOLE system, designed by the Centre National d'Études Spatiales of France, will measure the Doppler shift of a signal transmitted from a satellite to the balloon and back again and hence the angle between the propagation path and the tangent to the satellite orbit. Again, measurements taken at two positions of the satellite fix the position of the balloon, and similar measurements during the next orbit yield the wind averaged over the intervening period. The first major trial, involving 500 constant-level balloons each carrying small thermistor thermometers and light-weight aneroid capsules, was carried out in 1972. A target of ± 4 km has been set for the accuracy of location of a balloon.

The OPLE (Omega Precision Locating Experiment) system, designed by NASA, makes use of the very low-frequency (10-kHz) Omega navigational system which, because of its low attenuation and high phase-stability, affords world-wide coverage and very accurate phase measurements. The balloon would receive signals from two pairs, i.e. three, Omega ground stations and retransmit them to a satellite which would then relay them to a computer on the ground for calculation of the balloon's position. Two lines of position (hyperbolic isophase contours) are established by the phase differences between the signals from each of the two pairs of transmitters and the position of the receiver (balloon) is given by the intersection of these two contours. The very long base-lines between the ground stations result in the position contours

cutting nearly at right angles to give a fix that is expected to be accurate to within 1 mile by day and within 2 miles at night for almost all geographical locations. The balloon and satellite need carry only a simple transponder, and as the motion of the satellite, which acts only as a relay station, plays no part in determining the fix, it can be geosynchronous. By interrogating on 50 different frequencies simultaneously it might be possible for one geostationary satellite to interrogate a total of 2000 balloons each for 3 minutes every 2 hours. Three such satellites, one with its orbit inclined at 30° to the Equator, could achieve global coverage over each 24-hour period and interrogate a total of perhaps 6000 balloons.

However, because of the severity of the icing problem, to which no solution has yet been found, balloons can be flown economically only above 200 mb, and below 850 mb in the tropics, the most vital part of the troposphere being barred. Accordingly, it seems that the constant-level balloon will play a much less prominent role in World Weather Watch than once seemed likely, and this leaves the difficult problem of obtaining wind data in the tropics unsolved. It has been suggested, however, that a large constant-level balloon flying at, say, 100 mb, might release very light-weight dropsondes carrying transponders and fitted with parachutes that would drift with the wind, and that these could be located and tracked by a navigational system such as Omega. Such a system may be tested later this year.

Automatic weather stations on land, on buoys, and on ships. All three of the satellite systems just described are capable in principle of communicating with automatic weather stations on land, on anchored or floating ocean buoys, and on moving merchant ships. In all cases, identification and precise location will be easier than with balloons.

Several countries are developing automatic stations to report conventional surface weather observations. The Meteorological Office is about to put into operational service stations that measure pressure, temperature, humidity, wind-speed and direction, rainfall, visibility and sunshine, and can be interrogated either by radio or by a telephone call.⁶ Similar installations will also be tried out on merchant ships, where the tendency towards greater automation and smaller crews may make it increasingly difficult to obtain all the required information from voluntary observers.

Even so, there will be vast areas of the oceans almost devoid of ships, and here automatic stations on buoys are a possible solution. The Meteorological Office has designed and built an experimental buoy which carries sensors to measure air and sea temperatures, wind speed, humidity and pressure, and has operated satisfactorily in coastal waters for several months.⁷ However, the technical problems of making sensing and telemetering systems that will continue to work unattended for long periods on the high seas, and to do this at a cost which will allow them to be deployed in large numbers, are formidable. Major expenditure on buoy development is therefore not likely to materialize until other and cheaper solutions have been thoroughly investigated.

Conclusion. There is little doubt that the developments described in this paper will, over the next decade or two, lead to major changes in the methods and techniques of meteorological observation and measurement, and that the direct measurement of some of the basic atmospheric parameters will be gradually supplemented, and perhaps ultimately replaced, by indirect methods

involving the remote sensing of electromagnetic radiations from atmospheric constituents by satellites. For the next 10 years or so, the global observing system will probably consist of a mixture of satellites, conventional radiosondes, dropsondes, balloons released from ground stations and ships and tracked by navigational aids such as LORAN and OMEGA, constant-level balloons carrying accurate radar altimeters, etc. However, satellite methods are likely to become more and more dominant, and although it may be necessary to retain some ground-based sounding stations for the calibration and checking of the satellite systems, it will probably be possible to dispense with many of the radiosonde stations in the northern hemisphere and the weather ships well before the end of the century.

A more detailed account of techniques and instruments for the remote sounding of the atmosphere is given in an excellent review by Houghton and Taylor.⁸

REFERENCES

1. MASON, B. J.; The GARP Atlantic Tropical Experiment. *Bull Wld Met Org, Geneva*, **22**, 1973, pp. 79-85.
2. ABEL, P. G. *et alii*; Remote sounding of atmospheric temperature from satellites II. The selective chopper radiometer for Nimbus D. *Proc R Soc, London, A*, 1970, **320**, pp. 35-55.
3. BARNETT, J. J. *et alii*; The first year of the selective chopper radiometer on Nimbus 4. *Q J R Met Soc, London*, **98**, 1972, pp. 17-37.
4. SMITH, W. L.; Vertical distributions of atmospheric water vapour from satellite infra-red spectrometer measurements. *Appl Optics, Easton, Pa*, **9**, 1970, pp. 1993-1999.
5. RODGERS, C. D.; Remote sounding of the atmospheric temperature profile in the presence of cloud. *Q J R Met Soc, London*, **96**, 1970, p. 654.
6. DAY, G. J., SANDS, K. J. T. and TONKINSON, B.; The Meteorological Office Weather Observing System Mk 2. Submitted to the *Meteorological Magazine*, London, for publication later in 1974.
7. SANDS, K. J. T.; The Meteorological Offshore Buoy Observing Experiment 1972. *Met Mag, London*, **103**, 1974, pp. 150-156.
8. HOUGHTON, J. T. and TAYLOR, F. W.; Remote sounding from artificial satellites and space probes of the atmospheres of the earth and planets. *Rep Prog Phys, London*, **36**, 1973, pp. 829-919.

551.554(267.3+676): 551.577.37

AN EXTREME WIND SPEED IN THE LOW-LEVEL JET-STREAM SYSTEM OF THE WESTERN INDIAN OCEAN

By J. FINDLATER

(East African Meteorological Department Headquarters, Nairobi, Kenya)

Summary. This note records an occurrence of very strong winds at one location affected by the low-level jet-stream system of the western Indian Ocean. The maximum speed recorded at 1000 metres above mean sea level exceeded all previously known values, and the strong winds were followed by excessive rainfall on parts of the coast of eastern Africa.

Introduction. Attention has been drawn in earlier papers^{1, 2} to the strong air current which circulates at low level over the western Indian Ocean and parts of eastern Africa during the months of the northern summer. The general form of the current is shown in Figure 1 which is a simplified version of a much more detailed analysis.³ The phenomenon is well marked from April to October every year, but it only protrudes north of the Equator from May until September. It is within the hatched area of Figure 1 that mesoscale low-level jet streams are commonly (though not exclusively) found on a daily basis, orientated in the direction of the major streamline and moving along it.

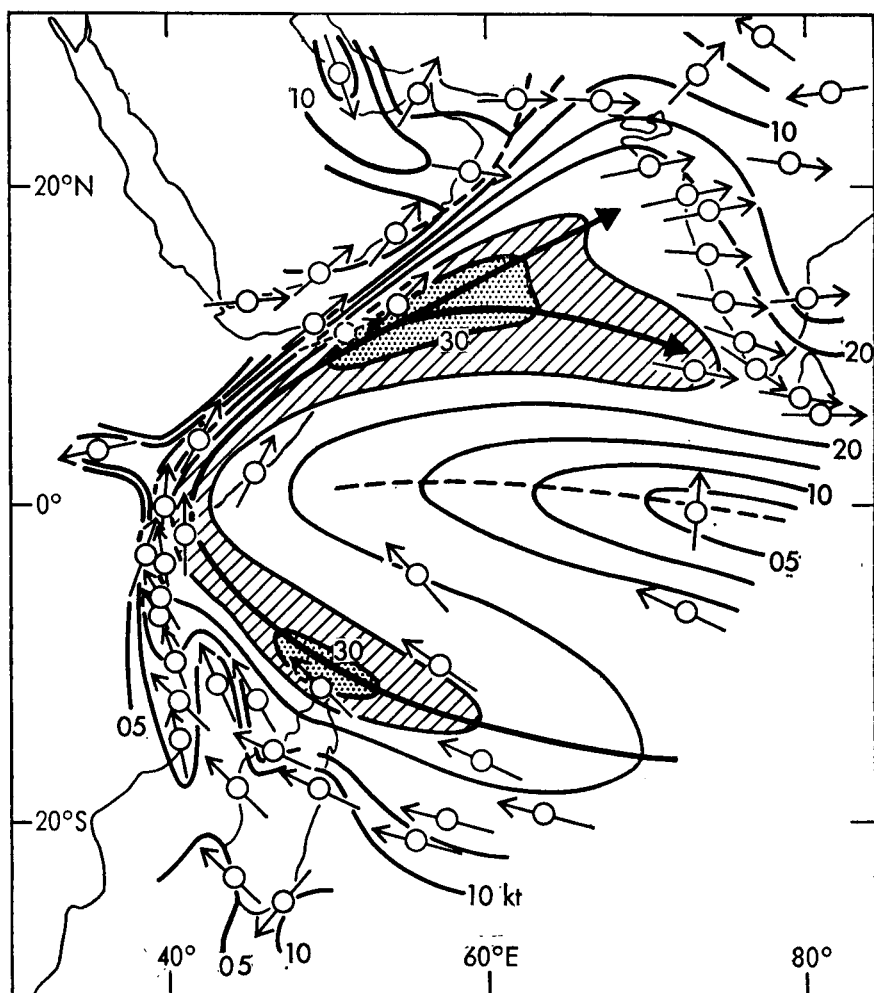


FIGURE 1—MONTHLY MEAN AIRFLOW AT 3000 ft (1 km) IN JULY

- Major streamline, axis of maximum flow.
- Isotachs, at intervals of 5 kt.
- Axis of minimum wind.

The core of the current lies about 1000–1500 metres above sea level and has a mean monthly speed of 25–35 kt* along most parts of its length. This core can, however, attain daily speeds of 50–100 kt or more; the three highest values previously measured were 98 kt by pilot balloon and 100 kt by an aircraft, both over eastern Kenya, and 105 kt by pilot balloon at Ras Asir, Somalia.⁴ Now an extreme speed of 126 kt at 1000 metres above mean sea level has been reported from Diego Suarez (12° 21'S, 49° 18'E, 105 m above mean sea level) on the northern tip of the island of Madagascar.

Upper winds at Diego Suarez, 1–4 October 1972. The mean upper wind at 1000 m in July at Diego Suarez is 135 degrees 30 kt. Between April and

* 1 kt = 0.5148 m/s.

October it varies only between 125 and 135 degrees in direction and between 21 and 30 kt in speed.³ Nevertheless the speed of the core at Diego Suarez can accelerate to very high values at any time during these months. One extreme value is considered here, but the report is credible because of the sequence of upper winds which preceded it.

During this period no cyclonic disturbances affected the area, and the usual broad south-easterly airstream prevailed. Satellite cloud photographs showed a long streak of low cloud orientated south-east to north-west across Diego Suarez, with its origin some hundreds of miles* to the south-east over the Indian Ocean. Calculations of the vertical velocity around the core of this current,⁵ where it passes over eastern Africa, have indicated that the air in the core is generally rising, with descent to either side. The core of the current is therefore more likely to be cloudy than areas on its flanks, and such cloud streaks have been found to be helpful in locating zones of high speeds in routine analysis and forecasting.

The upper winds recorded at Diego Suarez are shown in Table I as a time series and the following points are noteworthy:

- (a) The direction of the high-speed flow was relatively constant from 130 degrees, and the core of highest speed varied little from a height of 1000 m.
- (b) Seven consecutive soundings, including two radar-wind soundings, reported core speeds over 60 kt.
- (c) Five consecutive soundings, including one radar-wind sounding, reported core speeds over 80 kt.
- (d) Vertical wind shear near the surface was remarkable, even during the afternoons (local time is 4 hours in advance of Greenwich Mean Time).
- (e) Wind speeds dropped rapidly during the evening of 3 October 1972, but the direction remained unchanged.

The extreme speed of 126 kt at 1000 m is the highest value known to have been recorded anywhere in the low-level jet-stream system. Although this value may be a little exaggerated, because of possible errors in the pilot-balloon technique, it should be noted that the radar winds (maximum 92 kt) are averaged over deeper layers of air, and most probably undervalue the true maximum speeds, when, as in this case, the cores are shallow and are below the level at which maximum winds are specially reported in the coded message.

Although Madagascar lies aslant the south-easterly airstream, and there is some topographical intensification of the flow, it has been shown earlier² that low-level jet streams exist over the open ocean to the east and south-east of Madagascar, and that the phenomenon is not entirely due to topography.

During the period of these very strong winds excessive rainfall occurred on the east African coast near Mombasa (04° 02'S, 39° 37'E), close to the position where the axis of maximum flow approached the coast, although there is no evidence that strong winds at low level occurred over mainland Africa.

The maximum daily fall at Mombasa was 88.0 mm on 5 October, and the maximum three-day fall (3–5 October) was 166.3 mm, also at Mombasa. Figure 2 shows the flow at 1500 m, rather above the level of maximum wind, for 3 October 1972, and the area of heavy coastal rainfall with which the strong wind belt was, in some way, associated.

* 1 mile $\approx$ 1.6 km.

TABLE I—TIME SERIES OF SURFACE AND UPPER WINDS AT DIEGO SUAREZ, MALAGASY REPUBLIC, 1-4 OCTOBER 1972

Day in October 1972	01	01	01	02	02	02	03	03	03	04	04	04
Time GMT	0505	1105	2300	0515	1125	2300	0505	1105	2300	0505	1110	2300
Method	P.B.	P.B.	RAWIN	P.B.	P.B.	RAWIN	P.B.	P.B.	RAWIN	P.B.	P.B.	RAWIN
Surface	120 16	100 22	120 19	120 10	120 28	120 26	120 20	100 14	120 10	120 21	100 21	120 06
Height above mean sea level (metres)												
200	126 37	128 70	130 37	146 42	137 77	120 52	134 45	124 60	120 18	135 18	130 25	120 15
500	128 40	130 57	140 65	145 45	135 94	130 89	136 62	126 113	130 35	132 38	135 32	120 26
1000	121 35	143 43	130 73	129 80	134 108	120 90	128 87	127 126	130 37	132 27	131 42	120 31
1500	113 47	114 32	120 64	107 72	119 60	120 91	118 70	124 85	140 30	122 43	107 38	120 30
2000			100 37	100 60	100 49	110 92	092 68		130 17			120 33
2500			110 30			080 62	076 43		140 10			110 23
3000			110 26			040 41	066 36		130 13			120 10

Station co-ordinates: 12° 21'S, 49° 18'E, 105 metres above mean sea level.

P.B. = Pilot balloon wind. RAWIN = Radar wind.

Winds are given in degrees true and knots. Bold type indicates that the wind speed reached or exceeded 80 kt.

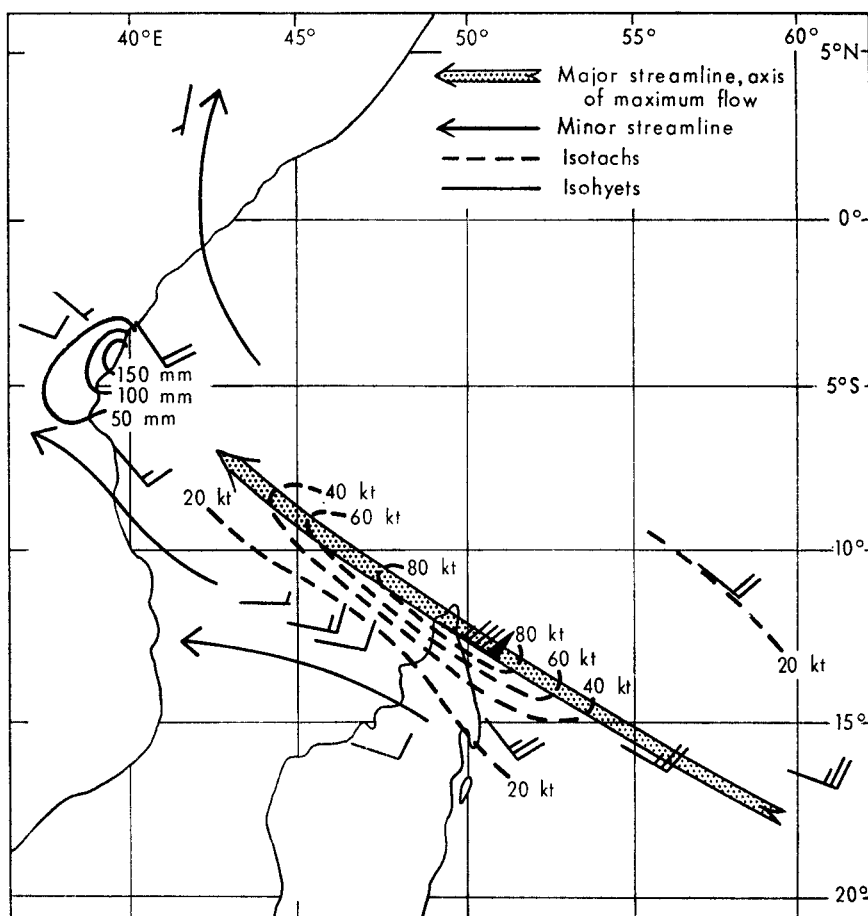


FIGURE 2—WIND FLOW AT 1500 m (850 mb) AT 12 GMT ON 3 OCTOBER 1972
Isohyets are for total rainfall, 3, 4 and 5 October 1972.

Acknowledgements. The assistance of the Director of the Meteorological Service of the Republic of Malagasy, who kindly provided the complete time series of verified upper winds from Diego Suarez, is acknowledged.

This note is published by permission of the Director-General of the East African Meteorological Department.

REFERENCES

1. FINDLATER, J.; Cross-equatorial jet streams at low level over Kenya. *Met Mag, London*, **95**, 1966, pp. 353-364.
2. FINDLATER, J.; A major low-level air current near the Indian Ocean during the northern summer. *QJR Met Soc, London*, **95**, 1969, pp. 362-380.
3. FINDLATER, J.; Mean monthly airflow at low levels over the western Indian Ocean. *Geophys Mem, London*, **16**, No. 115, 1971.
4. FINDLATER, J.; The strange winds of Ras Asir. *Met Mag, London*, **100**, 1971, pp. 46-54.
5. FINDLATER, J.; Aerial explorations of the low-level cross-equatorial current over eastern Africa. *QJR Met Soc, London*, **98**, 1972, pp. 274-289.

REVIEW

Climatologie—Méthodes et Pratiques, 2e édition, by R. Arléry, H. Grisolle and B. Guilmet. 240 mm × 150 mm, pp. xvii + 434, *illus.*, Gauthier-Villars Éditeur, 24–26 Boulevard de l'Hôpital, 75005 Paris, 1973. Price (paperback): 90 F.

Within its limitations, this is a good book. The authors, three senior members of the French Meteorological Service, state that it is intended as a textbook for scientists intending to work in a national climatological service, and for users of climatological information, and the newcomer in either category who reads and absorbs the contents will find that he has learned a great deal which will stand him in good stead, and not much which he will realize later to have been a waste of time. But it needs to be supplemented.

After an introduction in which the objectives are set out and the definition of 'climate' is discussed, the individual climatic elements are described. In the second part, which makes up about half the book, the statistical methods open to the climatologist are discussed with practical examples, mostly based on French data, which may be new to English-speaking readers. The coverage of methods is excellent, although the chi-square distribution might have been given a little more attention, and there is a good chapter on normals. Tricky points like persistence, temporary oscillations, and loss of degrees of freedom, are brought out into the open and not glossed over, although the reader still has to decide how he deals with them. The third part, on applied climatology, illustrates most of the worthwhile methods of presenting climatological information in assimilable form.

The limitations of the treatment arise because the authors seem to have had no opportunities for working with electronic computers. In consequence, the possibilities which exist for making climatic predictions, and for understanding climatic processes, which depend on powerful means of data processing, are not really envisaged. For example, the method of filtering is treated only sketchily, while principal-component analysis and Monte Carlo techniques do not seem to be considered at all, but there are detailed descriptions of punched-card apparatus which by 1974 should have been retired to a museum. The new concepts involved in computer work, such as the emphasis on a regularly arranged digitized data bank, and modular computer programs to work on the data bank, and on the ability to supply, at low cost, statistics adapted to the customer's need; these ideas are missing from the present treatise, although they must assuredly enter into the mental stock-in-trade of the climatologists of the future.

Apart from the computer topics there are plenty of references, and the authors show familiarity with a great deal of the English-language climatic literature. Possibly for this reason, the whole book is written in a style of French which the reviewer found most pleasant and easy to follow. Taken as a whole, the treatise merits the reflection that if the authors could produce an English translation with the help of a computer-minded collaborator who could add about 100 pages on the computer topics, the result would be valuable to the meteorological community for a very long time to come.

J. M. CRADDOCK

LETTER TO THE EDITOR

Wet-bulb freezing level as a snow predictor

A paper by Mr B. J. Booth¹ shows a relationship between the wet-bulb freezing level and his index for snow prediction. In a subsequent letter² Mr F. E. Lumb says it is unfortunate that I did not include wet-bulb freezing level as one of the predictors examined in my paper³ on the subject.

The main reason for the omission is given on page 355 of the paper, where I claim that on most occasions the dew-point depression is so small that humidity can be ignored in deciding whether rain or snow is the more likely. On the other hand, Mr Lumb refers to the outstanding usefulness of the wet-bulb freezing level 'on those memorable occasions when snow descends well below' its initial height. This may be true, but the trouble is that such events tend to be memorable because they were not forecast.

It is important to remember that the discovery of an index that is related to the probability of snow may represent only a small contribution to the forecasting problem. Such a predictor is worthless unless it is either (a) a number which is known at the time when the forecast is made or (b) a number which can be forecast with a fair degree of accuracy.

If neither of these conditions is fulfilled a correlation between a weather element and an index does no more than enable the forecaster to state his problem in different terms. An example of such an index is the surface temperature, which might be quite a useful snow predictor were it not for the fact that the temperature itself is affected by whether the precipitation is rain or snow.

Mr Booth is clearly aware that his two papers on snow predictors, like mine, are concerned mainly with establishing correlations. These were correlations between simultaneous elements and were arrived at objectively. It would have been impossible to give them more than an indication of their usefulness as forecasting tools because such assessments are bound to be subjective. Only by experience can the individual forecaster find out what method is the most useful to him.

C. J. BOYDEN

Guildford,
Surrey

REFERENCES

1. BOOTH, B. J.; A simplified snow predictor. *Met Mag, London*, 102, 1973, pp. 332-340.
2. LUMB, F. E.; Wet-bulb freezing level as a snow predictor. *Met Mag, London*, 103, 1974, p. 59.
3. BOYDEN, C. J.; A comparison of snow predictors. *Met Mag, London*, 93, 1964, pp. 353-365.

Editor's comment. This correspondence is now temporarily closed pending the forthcoming publication of a full article on this topic by staff of the Forecasting Techniques Section of the Meteorological Office.

NOTES AND NEWS

AUTOMATIC CHART PLOTTING

Following a successful series of field trials, an operational trial of automatic chart plotting was started in November 1973. In this trial most of the three-hourly and six-hourly charts required by the Central Forecasting Office for the period 0900–1800 are being plotted automatically from computer-processed data. Owing to the tight time schedule the automation of some of the charts must await the implementation of the electronic interface between the Telecommunications Branch and the main IBM computer.

PUBLICATION RECEIVED

Sea and air—the marine environment, second edition, by Jerome Williams, John J. Higginson and John D. Rohrbough. 255 mm × 165 mm, pp. xx + 340, illus., Naval Institute Press, Annapolis, Maryland, U.S.A., and Patrick Stephens Limited, Bar Hill, Cambridge CB3 8EL, 1973. Price: £6.00.

OFFICIAL PUBLICATION

British Rainfall Supplement 1961–1965. (London, HMSO. Price: £7.)

This is the first edition of the supplement to *British Rainfall* foreshadowed in *British Rainfall* 1961.

Part I, the Table of Rainfall Stations, lists all stations for which one complete year of rainfall data has been published during the years 1961 to 1965, also the first calendar year with data available for these stations. Complete station particulars are given, some of which have been omitted from the annual volumes of *British Rainfall* since 1961 in order to make way for more rainfall data. Where known, the wettest day on record is included for those stations where daily records are maintained.

Part II of the supplement contains obituary notices of voluntary rainfall observers who have co-operated with the Meteorological Office for 35 years or more.

Part III contains a summary of the work of the hydrometeorological branch of the Meteorological Office during the 5 years.

Part IV deals with heavy rainfall. It contains a summary of the Bilham classification of heavy falls of rain and summaries of heavy falls of rain on rainfall days.

Part V is devoted to special articles by individual authors. There are two articles, 'The presentation of monthly rainfall' by A. Bleasdale and 'Accumulated percentage departures of average rainfall' by P. M. Stephenson.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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SOME EXAMPLES OF THE RAINFALL FORECASTS PRODUCED BY THE FINE-MESH VERSION OF THE 10-LEVEL MODEL

By P. G. WICKHAM

Summary. The rainfall forecasts over the British Isles, computed by the fine-mesh version of the 10-level model on four occasions during the summer of 1973, are displayed.

Current deficiencies in the formulation of certain physical processes in the model, notably the representation of convective rainfall processes and of topography, give rise to some substantial, but identifiable, errors in the rainfall accumulations forecast at individual grid points. However, from a synoptic viewpoint the computed forecasts often provide useful guidance on the character of the rainfall occurring in these situations.

The fine-mesh version of the 10-level model. A detailed description of this model was published in 1971.¹ Since that date a number of changes in the formulation of the fine-mesh model have been introduced, notably the adoption of a semi-implicit integration scheme. However, the modelling of the precipitation processes remains unchanged. At each time-step in the integration of the forecasting equations, equivalent to 12 minutes of real-time, forecasts of the rate of rainfall at the bottom level of the model (1000 mb) are made at each point of a horizontal grid which has a mesh size of 100 km. The accumulated rainfall total since the start of the forecast run is also recorded.

The forecast rainfall is produced in the model in two ways. Advection of water vapour by the three-dimensional motion of the model atmosphere may lead to the air at some level above a grid point becoming supersaturated. The superfluous moisture then condenses, falls and, subject to possible evaporation into drier layers below its original level, reaches the surface as rain. Rainfall produced in this way is referred to as 'dynamic rain'.

A superfluity of moisture in a layer above a grid point may also be produced as a result of the 'convective adjustment' process. This is a process, carried out after each time-step, in which the thicknesses of each successive pair of layers above a grid point are mutually adjusted so as to ensure that no unreasonable static instability develops at individual grid points. Since, in the current formulation of the model, the relative humidities of the adjusted layers are kept unchanged, any moisture in excess of that required to conserve the relative humidities is condensed and may eventually reach the surface. This is referred to as 'convective rain'.

It has been found in practice that, while the 'convective rainfall' forecast by the model normally occurs in areas where it is synoptically reasonable to expect showers, the quantity of convective rain forecast is usually very much less than the quantity of forecast dynamic rain and also very much less than the actual rainfall which occurs through showers or other convective systems.

The 'total rate' of rain at any grid point is the sum of the dynamic and convective rates. In this article it is the total rate of rain and the total rainfall accumulations that are displayed.

General synoptic character of the early summer of 1973. For many months prior to June 1973 the weather in the British Isles was remarkably dry. During the first 10 days of June this dry weather continued and led to public warnings becoming increasingly frequent during this time, about the necessity of conserving water supplies.

Subsequently, during the following three weeks, there were four important frontal situations which affected the country. In terms of the actual rainfall accumulations, two of these situations were significantly wet in the southern half of England but dry elsewhere, while the other two were dry over England but brought rain to Scotland. Having regard to the national water shortage at this time, it was of some importance to be able to forecast correctly which of the fronts would produce a lot of rain and which would not.

An assessment of the synoptic value of the charts of forecast rates of rainfall. In this section some brief comments are made on each of the forecast charts in Figures 1-4, to illustrate their value to forecasters engaged on general synoptic duties. Each chart has also been given an assessment letter which, being subjective, is not likely to command universal agreement. However, the point of these assessment letters is to provide an indication of the value of the forecasts as a whole rather than individually. This is done in Table I. The definitions of the letters are to be found on page 212.

Figures 1-4 illustrate each of the four frontal situations in turn. Each covers a 48-hour period and shows actual charts at 12-hour intervals. The isobars are drawn at 4-mb intervals and the frontal positions have been taken from the *Daily Weather Report*. The extent of the frontal rain has been sketched in from the reported synoptic observations, thus distinguishing areas of mainly slight rain (hatched), mainly moderate rain (cross-hatched) and showers (symbols). Beneath each of the actual charts are the 24-hour and 36-hour prognostic charts which verify at that time. On these, the forecast rainfall is shown at each grid point by symbols (+, ○, ■) which distinguish slight, moderate and heavy rates of rain respectively. In order to keep the patterns of the main frontal rain belts as clear as possible, forecast occurrences of very slight rain (less than 0.1 mm/h) have been omitted.

Verification time	Forecast chart	Comments	Assessment letter
		(Charts on Figure 1)	
00 GMT 12/6/73	T+36	The rain area over Scotland is too far south, but this is not a misleading forecast. The main fault is the weakness of the pressure gradients.	B
	T+24	The rain in Scotland is well placed and the intensity seems about right.	A
12 GMT 12/6/73	T+36	The cold front is correctly placed over Ireland and the extensive area of moderate rain over northern Scotland is quite realistic.	A

Verification time	Forecast chart	Comments	Assessment letter
00 GMT 13/6/73	T+24	The intensity of the narrow, weakening cold front is well forecast but it is a little slow, being about 1 grid length too far north. No convection over Ireland was forecast.	B
12 GMT 13/6/73	T+36	On both these forecasts the pressure trough over north-west Europe has been moved too slowly, but the rapid stabilization of the air over the British Isles and transition from cyclonic to anticyclonic curvature of the isobars, coupled with the absence of any rain, was well forecast.	A
	T+24		A
00 GMT 19/6/73	T+36	(Charts on Figure 2) The forecast rainfall pattern suggests an active warm front over north-east Scotland and a weaker cold front over western Ireland. The cold front is too slow by at least 1 grid length, but is not totally misleading, for rain is forecast over Ireland as far south as 52°N.	C
	T+24	The location and intensity of the cold front rain are very well forecast.	A
12 GMT 19/6/73	T+36	The frontal rain is well placed over eastern Scotland but is some 2 grid lengths misplaced over southern England.	B
	T+24	Apart from the premature clearance of rain in eastern Scotland, this forecast is good.	A
00 GMT 20/6/73	T+36	The forecasts for this particular time are not in fact too badly astray, but this is a lucky chance. The model is not getting the full extent of the low pressure development over Belgium and there is no warning of the possible spread back of the rain from the North Sea into eastern England.	B
	T+24		B
12 GMT 20/6/73	T+36	These are incorrect and misleading forecasts. The model moves the rain trough slowly but steadily east—whereas the developing Belgian low remains stationary and its circulation brings extensive moderate or heavy rain back over a great part of the British Isles.	D
	T+24		D
00 GMT 27/6/73	T+36	(Charts on Figure 3) With the development of a pressure trough in about the right place and some isolated grid points giving rain, this forecast gets the correct 'weather type', but has only the poorest indication of the details.	C
	T+24	The location of the rain area over south-east England is remarkably good, though the intensity was under-forecast. The general line of the warm front in the English Channel and Biscay is discernible, though too far south.	B
12 GMT 27/6/73	T+36	Not a very convincing forecast chart, although ill-defined pressure patterns are typical of this weather type. The forecast rain areas bear little relation to reality.	D
	T+24	A substantial rain area over Brittany is forecast, about 1 grid length too far south.	B

Verification time	Forecast chart	Comments	Assessment letter
00 GMT 28/6/73	T+36	A remarkably good forecast, over both England and France, of the location of the frontal rain areas. The intensity over England is too weak.	A
	T+24	The northern boundary of the rain over England is about 1 grid length too far south, but otherwise this looks a good forecast for England. Over France the cold front movement is too slow.	B
12 GMT 28/6/73	T+36	Both these forecasts are quite good. Over England the location and intensity of the trailing rain area is well-handled, with the T+24 forecast being marginally more correct.	B
	T+24		A
00 GMT 1/7/73	T+36	(Charts on Figure 4) Quite a good forecast with some development of rain occurring in the pressure weakness to the south-west of Ireland. Over Scotland the cold front is not clearly forecast, but over southern Ireland it is quite well placed.	B
	T+24	An unimpressive forecast. No specific developments are forecast in the area south-west of Ireland and the frontal rainfall is too weak and disorganised to give any useful guidance.	C
12 GMT 1/7/73	T+36	Although the rain on this front progressively decreases, the complete lack of any significant rain at this stage is too premature a forecast.	C
	T+24	The ill-defined rain belt appears to be well placed but it is too weak, especially over the high ground of Scotland.	B
00 GMT 2/7/73	T+36	Another forecast of a too rapid cessation to the rain. The positioning is fairly good.	B
	T+24	This has got right the general impression of patchy outbreaks of rain on the weakening front but details of the intensity and location are wrong.	B
12 GMT 2/7/73	T+36	Evidence from the North Sea is sparse, but this appears to be a good forecast.	A
	T+24	A correct forecast of dry weather over the British Isles, but it is likely that some rain is still falling over the North Sea and this should have been shown.	B

In these assessments, the letters have the following meanings:

Letter	General character of the forecast chart	Forecast rain areas over the British Isles
A	Very good	Substantially correct in location and intensity
B	Good; gives useful forecast advice	Slight errors in either location or intensity
C	Fair, but not seriously misleading	Correct 'type'—but definite errors in both location and intensity
D	Poor	Major forecasting errors

Table I shows the frequency with which the various assessment letters occur on the four situations covered in this paper. The figures reflect a slight diminution in the overall usefulness of the prognoses as the forecast time increases from T+24 to T+36. But even at T+36 it is still possible to place two-thirds of the forecasts into categories A or B. At T+24 the proportion of such forecasts is higher, and the overall figure of the 23 out of 30 in categories A and B shows that at least 75 per cent of these individual forecast charts gave good, useful forecast advice.

TABLE I—ASSESSMENT OF THE SYNOPTIC VALUE OF THE FORECAST CHARTS

Forecast chart		Assessment letter				Total
		A	B	C	D	
	T+24	5	8	1	1	15
	T+36	4	6	3	2	15
	Total	23		7		30

The quantitative rainfall forecasts. Figures 5–8 show, for each occasion, the actual and forecast accumulations of rain during the ‘rainfall day’ extending from 09 GMT on Day 1 to 09 GMT on Day 2. The forecast values are plotted, in millimetres, from an array of 72 grid points covering the area of the British Isles. They are values computed during the forecast runs based on 00 GMT data on Day 1, and are the predicted accumulations between the (T+09) and (T+33) hours of these forecasts.

The actual accumulations are the average areal rainfall amounts over 100-km squares centred on the model’s grid-point locations. These values were produced by computer using the Comprehensive Areal Rainfall Program (CARP)² developed by the Agriculture and Hydrometeorology Branch of the Meteorological Office, in which an analysis is made of the daily rainfall totals from over 6000 rain-gauges covering England, Scotland and Wales. Since no measurements are available over the sea, the only grid squares for which reliable estimates of the actual accumulations can be made are those which lie entirely, or very largely, over land. There are only 17 such grid squares.

There can be little doubt that in the broadest terms these four situations were more or less correctly handled by the model. Figures 6 and 7 show the two occasions when wet weather was forecast for the south of the country, while Scotland remained dry; this proved to be correct. Figures 5 and 8 show the two occasions when the pattern was reversed; Scotland getting the rain while England remained dry. On these two occasions the forecasts were broadly correct, though Figure 8(b) is the least convincing of the four forecast charts.

However, when attention is transferred from the broad sweep of the synoptic-scale features discussed above, and is concentrated on individual grid points it is clear that a very different order of forecasting accuracy is attainable. A visual comparison of the forecast and actual values at corresponding grid points in Figures 5–8 is enough to convince one that the correlation is very small. Not only is the general level of the forecast rainfall below that of the actuals but there is also in each case an error in the location of the rain areas. These positional errors, though they may amount to only one or two grid lengths, are quite enough to produce large rainfall errors at individual grid points.

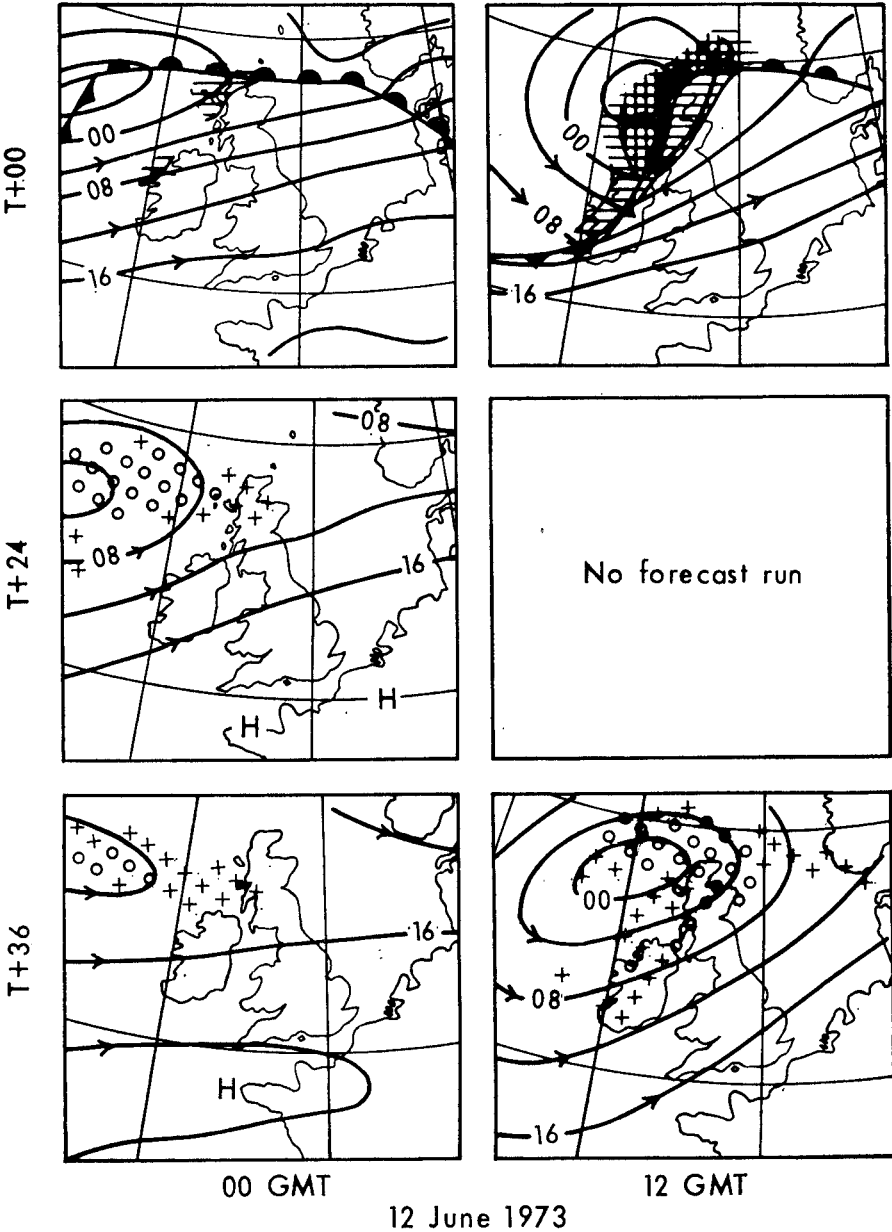


FIGURE 1—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 12-13 JUNE 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.

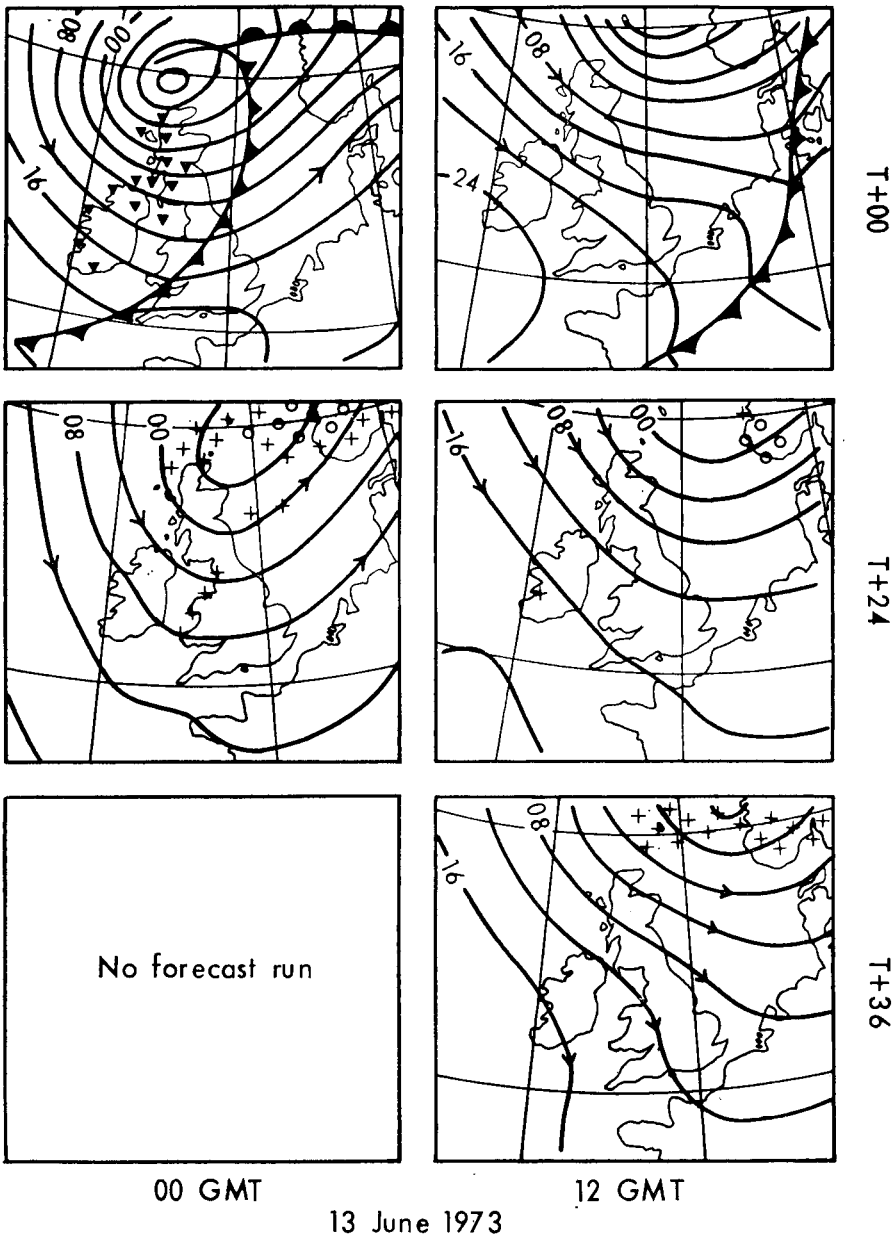


FIGURE 1 (continued)

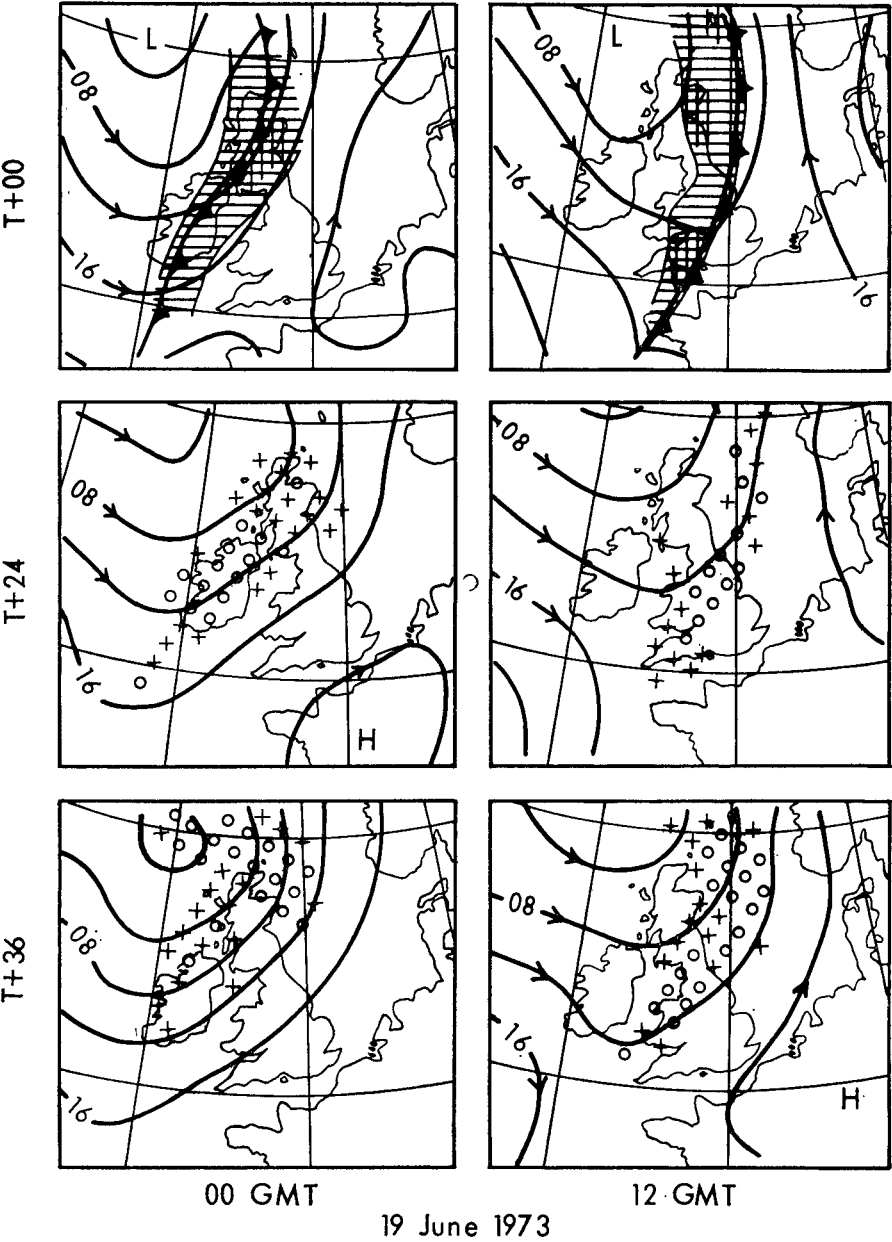
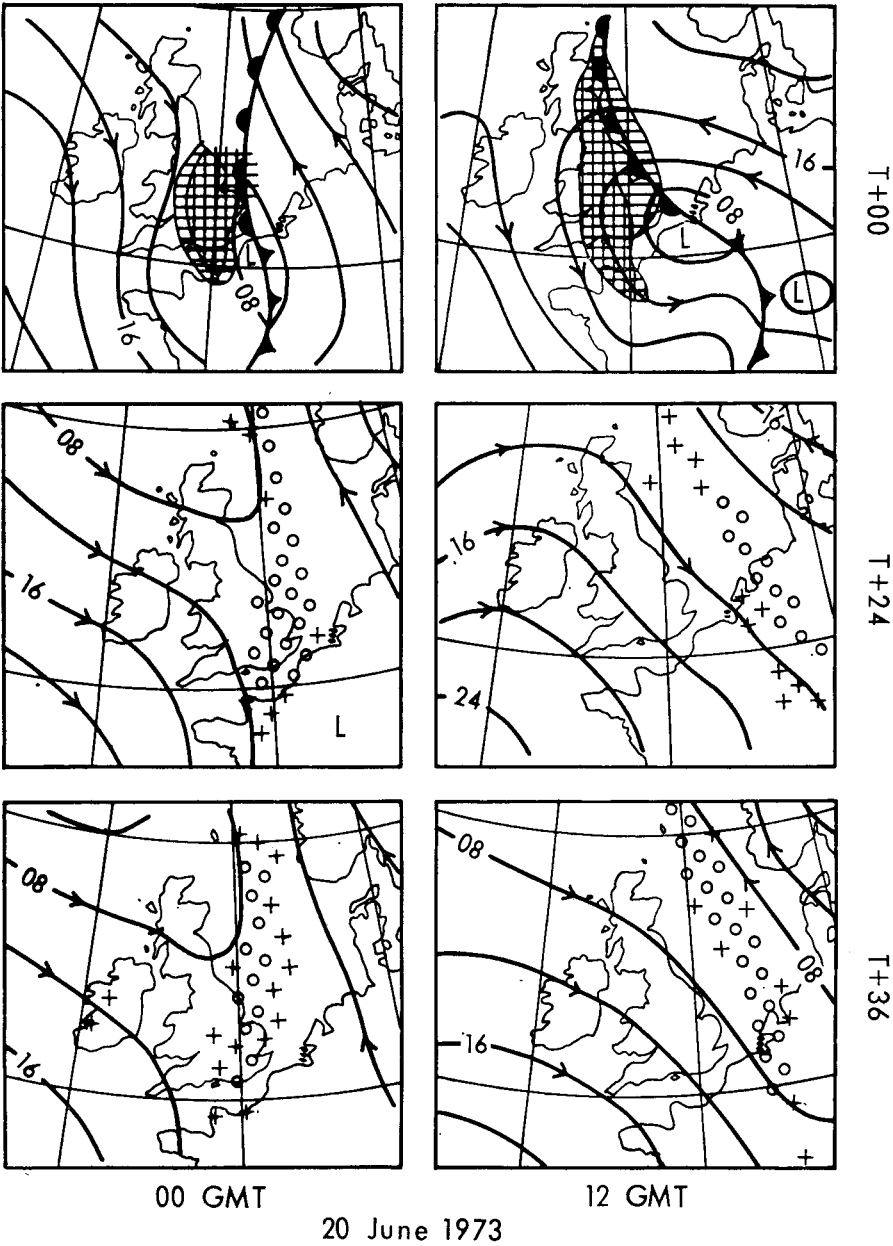


FIGURE 2—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 19–20 JUNE 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.



20 June 1973

FIGURE 2 (continued)

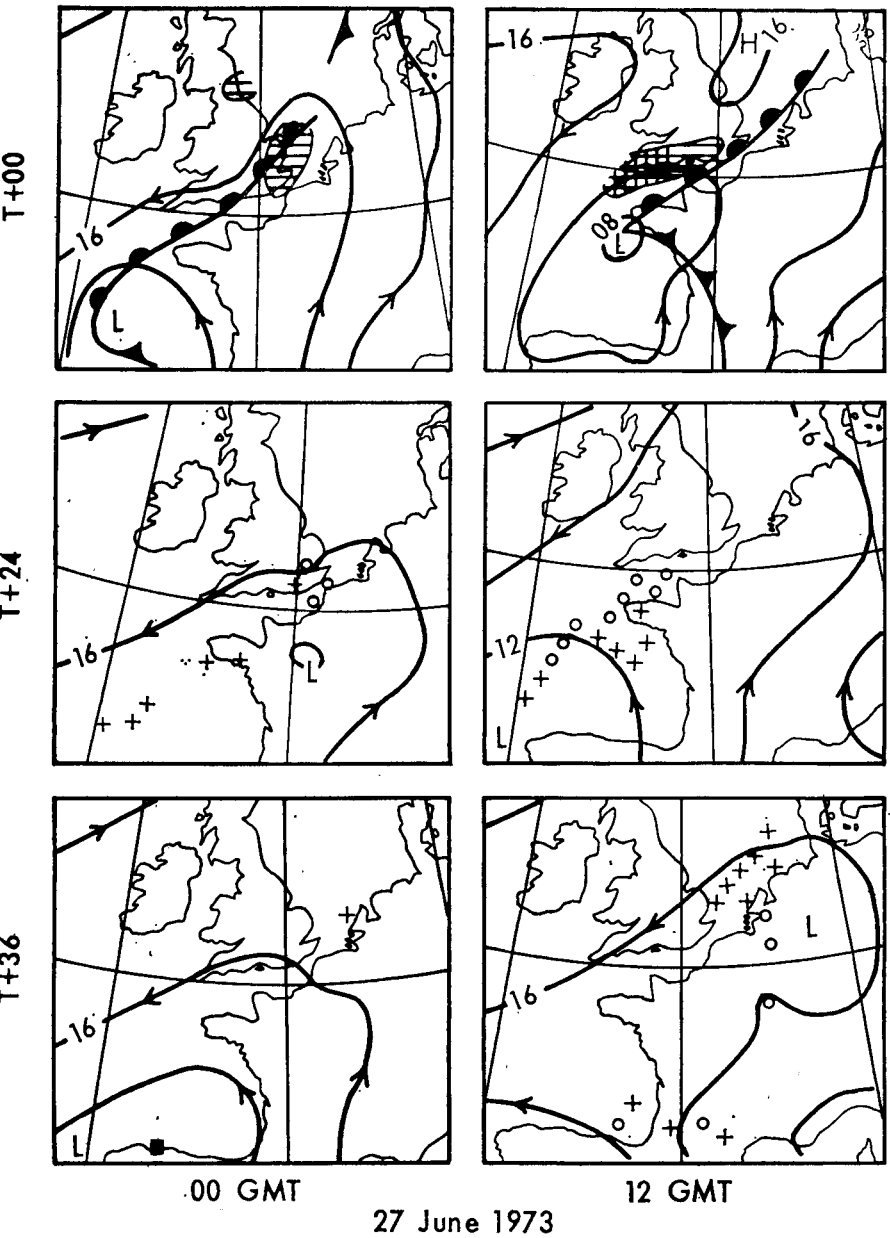


FIGURE 3—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 27-28 JUNE 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.

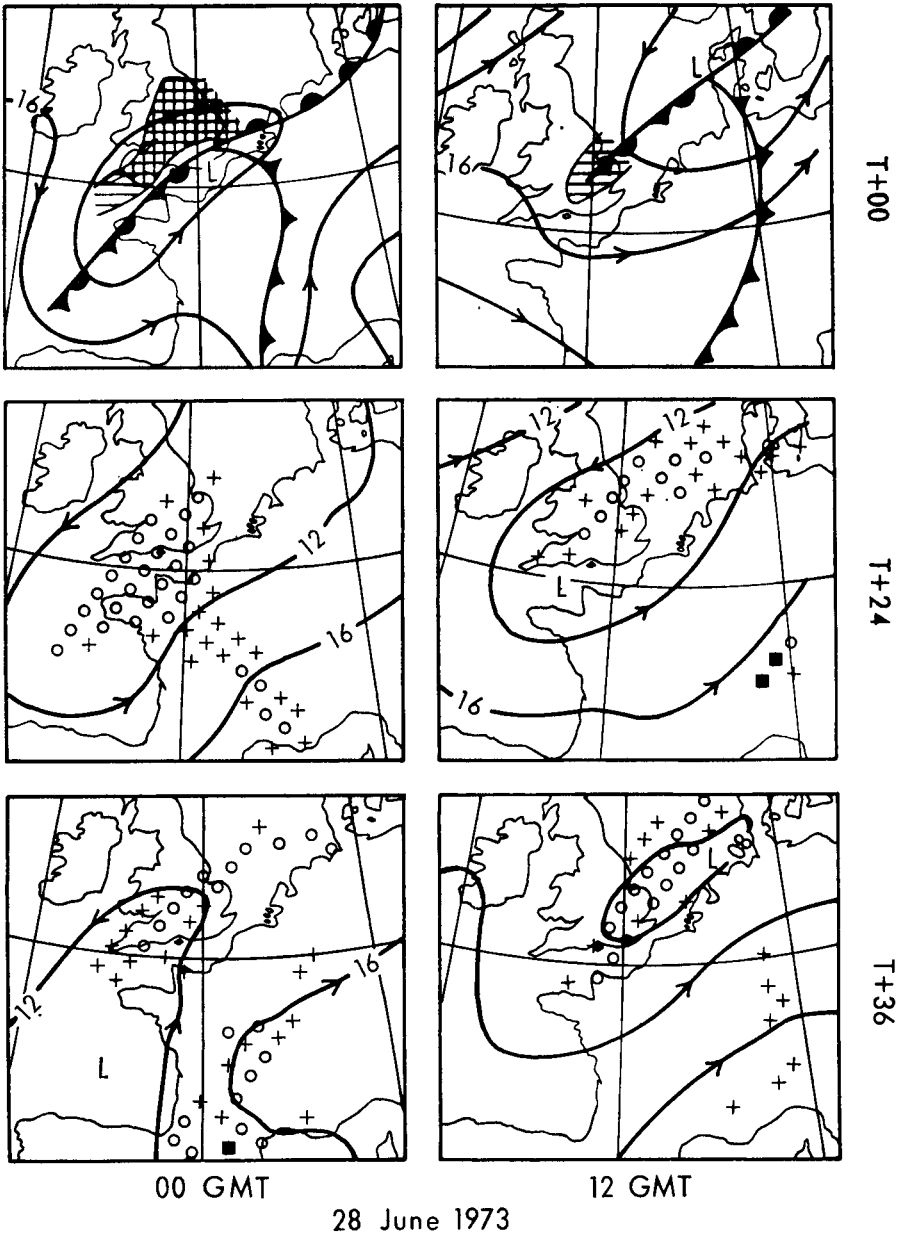


FIGURE 3 (continued)

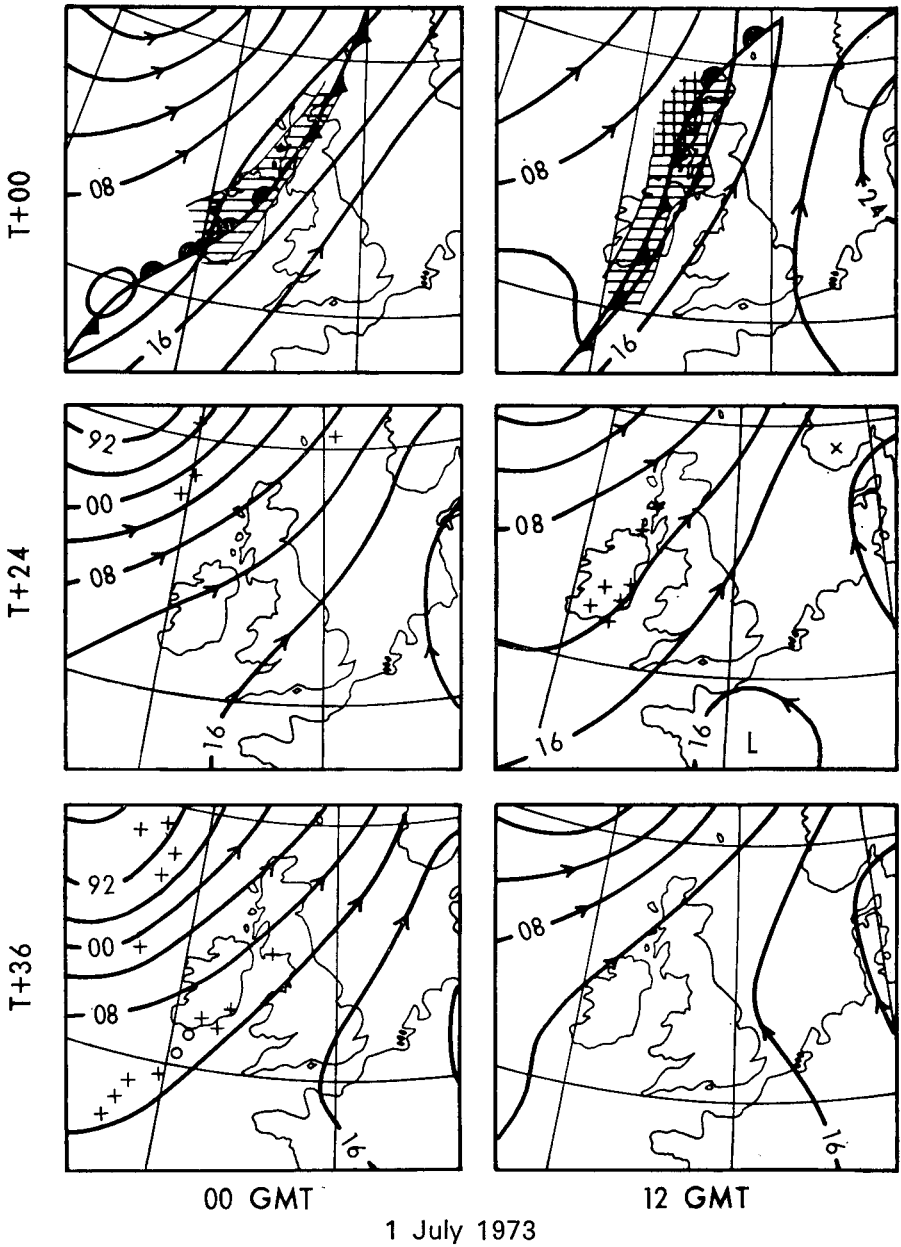


FIGURE 4—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 1-2 JULY 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.

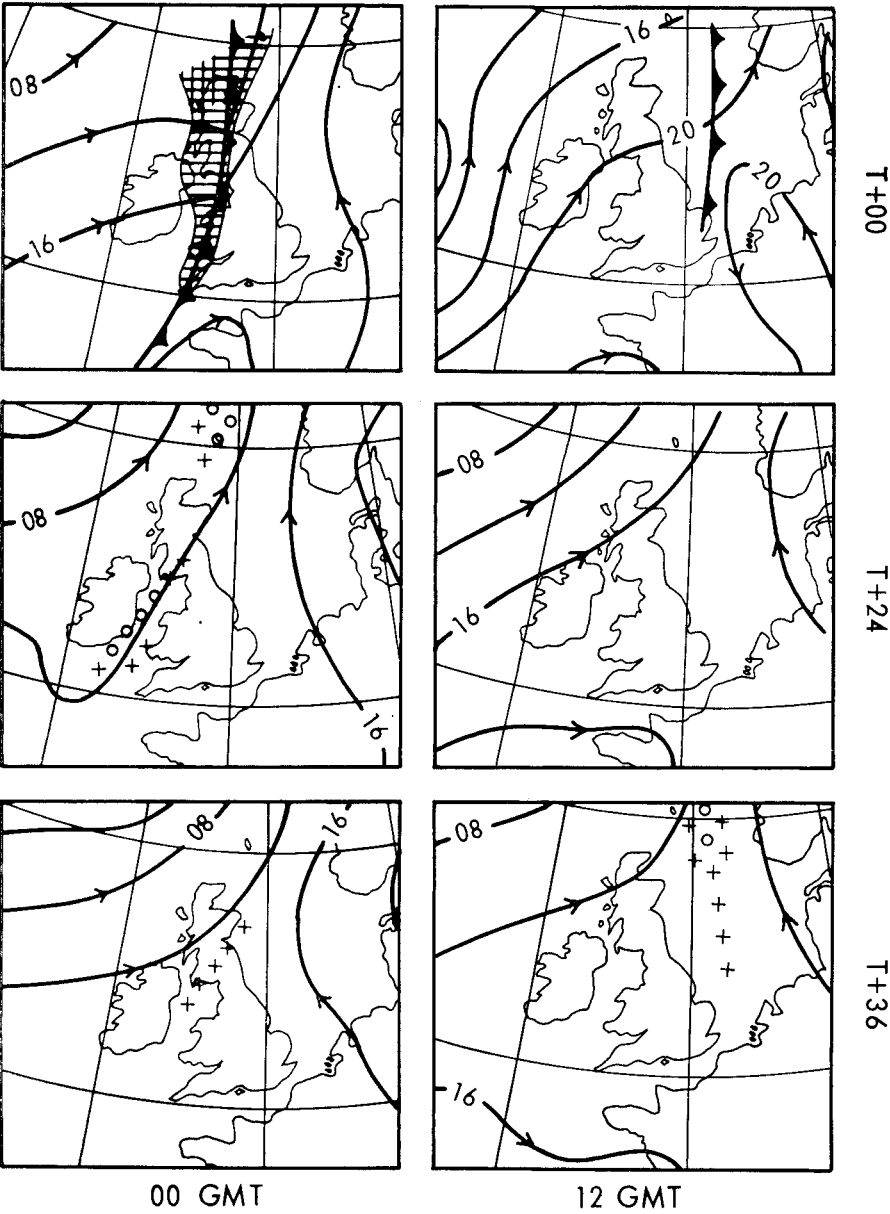
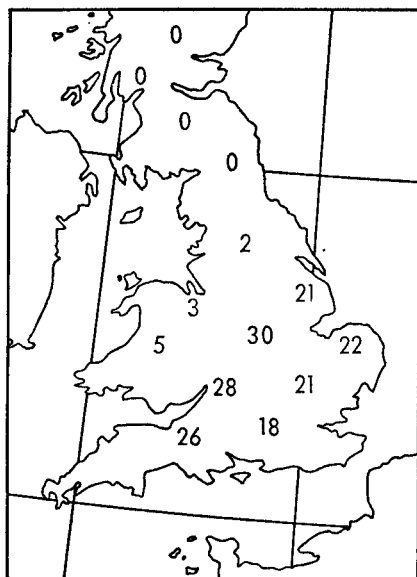
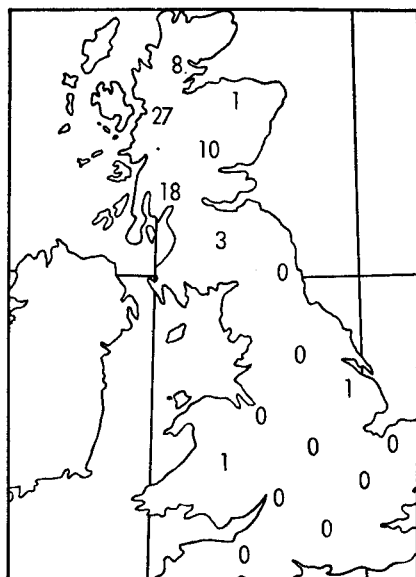


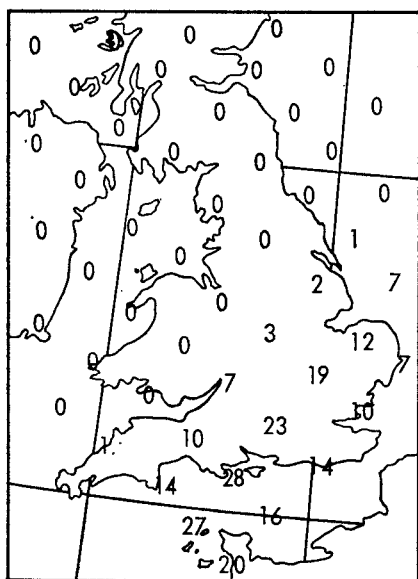
FIGURE 4 (continued)



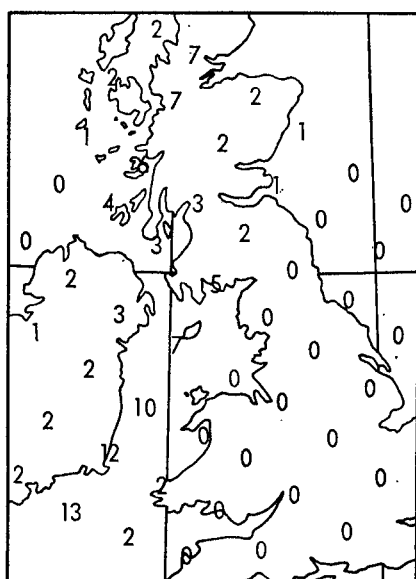
(a)



(a)



(b)



(b)

FIGURE 7—24-HOUR RAINFALL TOTALS
FROM 09 GMT, 27 JUNE 1973

FIGURE 8—24-HOUR RAINFALL TOTALS
FROM 09 GMT, 1 JULY 1973

(a) Actual values (mm) averaged over 100-km squares

(b) Forecast values (mm) at grid points

As far as it is possible to do so, with the limited information available on the actual charts, the most meaningful assessment of the value of Figures 5–8 is to list the errors occurring in the forecast location and magnitude of the maximum 24-hour rainfall total.

TABLE II—ERRORS OCCURRING IN THE FORECAST LOCATION AND MAGNITUDE OF THE MAXIMUM 24-HOUR RAINFALL TOTAL

Figure	Date	Highest rainfall at a grid point		Approx. distance between forecast and actual maxima
		Actual	Forecast	
		<i>mm</i>		<i>km</i>
5	12/6/73	36	14	140
6	19/6/73	39	22	180
7	27/6/73	30	28	220
8	1/7/73	27	7	50
	Mean values	33	18	150

Conclusions. The results show that, on the current performance of the 10-level model, the synoptic value of the rainfall forecasts is considerable. But as regards quantitative forecasting on the scale of one grid length the forecasts are of lower reliability. Errors in location of forecast rain areas are frequently about one or two grid lengths and the quantity of rain forecast by the model is generally only one-half to two-thirds of the actual values.

The reasons for particular forecasting errors are often quite difficult to pin-point with certainty. Sometimes an obvious fault can be traced, but usually it is the complex result of a number of factors whose effects are inter-related. At times there may be a lack of initial data, or there may be slight errors in the analysis of some crucial observations, or in their quality control. There are errors due to the approximations which have to be made when using finite difference methods to solve the mathematical forecasting equations. And there are errors due to the fact that most of the physical processes which occur in the real atmosphere are only modelled in an incomplete and approximate way in the computer programs. Some obvious indications of this are apparent in the charts displayed here, where the lack of a sufficiently detailed representation of topography in the model leads to serious underestimates of the rainfall over Scotland. It is also clear from the rainfall totals that the convective rainfall in the current formulation of the model is not sufficiently realistic.

The four actual charts in Figures 5–8 show that, even in these quite average frontal situations, rainfall gradients of over 1 inch (per rainfall day) per 100 km are not infrequent. With actual gradients of this magnitude it is clear that the misplacement of a rain belt by as little as one grid length on a forecast chart can result in large errors at some grid points. The achievement of high accuracy and reliability at this level of spatial resolution is a very formidable task.

REFERENCES

1. BENWELL, G. R. R., GADD, A. J., KEERS, J. F., TIMPSON, MARGARET S. and WHITE, P. W.; The Bushby-Timpson 10-level model on a fine mesh. *Scient Pap, Met Off, London*, No. 32, 1971.
2. SALTER, PAULINE M.; Areal rainfall analysis by computer. Geneva, World Meteorological Organization. Distribution of precipitation in mountainous areas, Vol. II, Geneva, 1972, pp. 497–509.

WINTER AND SPRING WEATHER AT RIYADH, SAUDI ARABIA

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Summary. The influence of synoptic-scale disturbances on the winter and spring weather at Riyadh is discussed with the help of seven examples from 1972. Hourly observations from the synoptic network in Saudi Arabia are used, together with surface and 500-mb charts and vertical time-section winds for 12 GMT. Small cyclonic circulations form over north-western Saudi Arabia and move east or south-east to the Persian Gulf. These cyclones either form on a cold front or a front develops within about one day. Heavy showers can occur when low-level moisture is advected either by southerly winds ahead of a cold front or by easterlies around the northern side of a centre.

Introduction. Little has been written about the synoptic meteorology of Saudi Arabia. Kuo,¹ in a general account, describes the dominance of southward-extending ridges of high pressure in the winter, interrupted by depressions moving eastward from the Mediterranean. Associated cold fronts, sometimes with rain or even thunder, become diffused as they cross the country; they are preceded by south-east winds (Arabic: *kaus*) and followed by north-westerlies (*shamal*), which in the east can be strong enough to give duststorms. Studies of individual rainy spells, in the east at Sharjah² and in the west at Jiddah,³ have shown the influence of developments in the upper troposphere on surface disturbances.

Until recently, the nature of synoptic disturbances over Saudi Arabia has been poorly understood, but the growing network of observing stations (Figure 1) now makes it possible to examine the disturbances more closely.

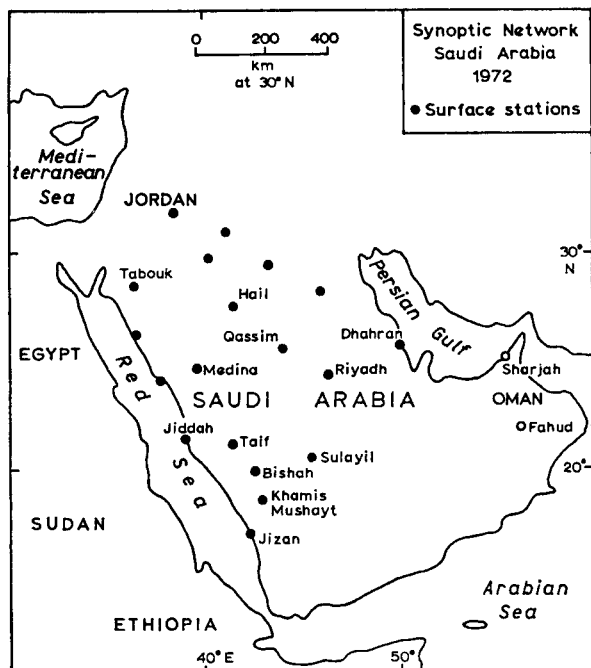


FIGURE 1—SYNOPTIC NETWORK IN SAUDI ARABIA AND OTHER PLACES MENTIONED IN THE TEXT

This paper describes some examples from the winter and spring of 1972, particularly their influence on the weather at the capital city, Riyadh (25°N 47°E).

Day-to-day changes. Time sequences of 12 GMT (1500 local time) observations at Riyadh show oscillations in pressure, wind and temperature with a periodicity of 2–8 days. In general, falling pressure is associated with rising temperatures and south-east winds, whereas rising pressure is associated with falling temperatures and north-west winds. A change from the former to the latter is sometimes sudden and resembles the passage of a cold front. On other occasions the change is more gradual, as though a cyclonic centre were passing nearby; south-east winds then either veer through south-west to north-west, or they back through north-east. Sometimes there is a spell of light and variable winds lasting a few hours. The reverse change, from north-west to south-east, is nearly always gradual, and is a veer through north-east, i.e. anticyclonic centres or associated ridges pass eastwards to the north of Riyadh.

The surface disturbances resembling cold fronts occur ahead of troughs in the upper westerly winds. Middle and high clouds are common, and sometimes there is occasional rain. High stratocumulus may accompany these clouds, but cumulus develops on days when there is a lower tropospheric inflow of moisture. Dew-points may then rise to 10°C, or even 15°C in spring. When south-east winds first develop as pressure starts to fall after a strong rise, dew-points are typically +5° to –5°C and low clouds are rare. Near pressure minima, where both dew-points and temperatures are usually above average, cumulonimbus clouds can develop, especially in the late afternoon, and lightning can occur well into the night. Thunderstorms are most likely between dusk and midnight, with squalls, sudden temperature falls and pressure rises, and sometimes dust-storms.

High dew-points can persist for about a day after winds have changed to northerly, but with a good rise of pressure and persistent northerly winds dew-points fall to 0° to –5°C.

The following examples illustrate the nature of disturbances affecting the weather at Riyadh. Emphasis is placed on time sequences of hourly observations, and on 12 GMT surface synoptic charts, but some idea of structure aloft can be obtained from changes in upper winds shown by vertical time-sections based on soundings at 00 and 12 GMT, and the deductions were checked by using 500-mb synoptic charts based on routine 12 GMT data.

11 January 1972. Surface synoptic charts showed that a depression moved east-south-eastwards to the north of Riyadh (Figure 2). A cold front passed between 15 and 16 GMT, with a wind veer from 200° 15 kt to 330° 20 kt and a temperature fall from 22° to 18°C; there was blowing dust from 11 to 19 GMT. The depression centre had moved north of Hail and Qassim, where the cold front passed soon after 13 GMT on the 10th and 06 GMT on the 11th respectively, and later it was overhead at Dhahran from 19 to 23 GMT on the 11th. The cold front was not clear-cut at Medina or Taif, but north to north-east winds set in at Sulayil during the night of 11th/12th (no observations were made there in 1972 between 18 and 05 GMT). Over the Red Sea, there was a weak push of north-westerlies to southward of Jiddah, and there was no evidence for the front reaching Fahud in the interior of Oman, where winds persisted from the south and south-east. Ahead of the front, large cumulus clouds had developed by

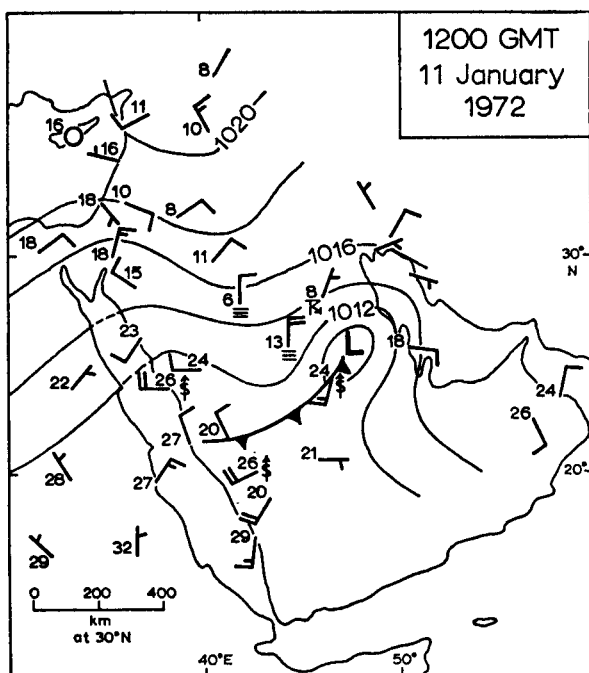


FIGURE 2—SURFACE CHART FOR 12 GMT ON 11 JANUARY 1972
Symbols show weather at 12 GMT or during the previous six hours.

12 GMT on the western escarpment, and there was some shallow cumulus or stratocumulus in the northerlies. A band of middle-level clouds lay north of Riyadh at 12 GMT, later giving 0.1 mm of rain there between 1605 and 1830 GMT.

The vertical time-section (Figure 3) showed the greatest changes in wind direction were confined to below 700 mb. Above that level, westerlies increased in speed with height, and direction changes suggested the eastward passage of a weak trough, its axis passing Riyadh early on the 12th. On the 500-mb charts, the axis was found to move from about 40°E at 12 GMT on the 11th to about 50°E on the next day. This trough was cold cored, temperatures at Riyadh being about 3 degC below those two days before and two days after at all levels to at least 200 mb.

29 January 1972. Again a depression moved east-south-eastwards to the north of Riyadh; it travelled at 35 kt and maintained a central pressure of about 1009 mb. After a short calm spell, winds picked up from the west between 07 and 08 GMT, becoming north-west at 20–35 kt after 10 GMT. The centre had moved over Hail between 18 and 21 GMT on the 28th and later cleared Dhahran by 09 GMT on the 29th. Its cold front passed Qassim 01–02 GMT on the 29th, and Taif 03–04 GMT, when westerlies changed to easterlies. Easterlies also set in at Sulayil between 17 and 18 GMT, and the front passed Fahud between 08 and 09 GMT on the 30th, where it was followed by north to north-west winds gusting to 30 kt. The front did not reach Khamis Mushayt.

On the 28th there was much middle-level cloud to the west and north of Riyadh, with outbreaks of rain which reached Riyadh during the night giving

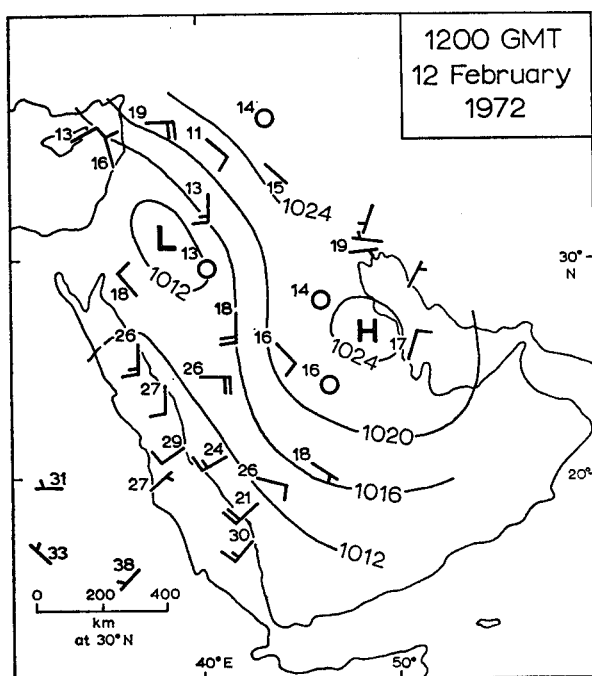


FIGURE 4—SURFACE CHART FOR 12 GMT ON 12 FEBRUARY 1972

19 February 1972. A depression moved eastwards to the north of Riyadh (Figure 5), with its cold front passing between 10 and 11 GMT, when winds veered from south to west, and then to north by 14 GMT. The centre had moved south of both Hail and Qassim and was over Dhahran by 14 GMT. Northerlies reached Sulayil during the following night, and north-easterlies reached Bishah although south-westerlies persisted at Khamis Mushayt. Dew-points at Riyadh were about 9°C in the northerlies but fell to near 0°C next day. Thus, moisture was advected from the Persian Gulf round the northern side of the depression, and it was associated with small cumulus and stratocumulus clouds.

Winds aloft suggested the passage of a trough at all levels up to at least 300 mb, crossing Riyadh at 500 mb during the latter half of the 20th, and with temperature falls of 10 degC in two days at 850 mb, decreasing upwards to about 3 degC at 300 mb; 500-mb charts showed that this trough had a large amplitude and was inclined from north-east to south-west.

22 March 1972. A cold front moved slowly south-eastwards towards Riyadh from 20 to 22 March (Figure 6). It was preceded by moist southerly winds with dew-points of 10–15°C, and followed by westerlies with dew-points about 0°C. Cumulus and cumulonimbus developed along and ahead of this front with much middle-level cloud giving outbreaks of rain, thunderstorms and dust-storms. Wind and temperature changes were erratic, presumably caused by downdraughts from the storms. Lightning was seen at Riyadh on the night of 20th/21st, and occasional rain on the 21st amounting to 17 mm was followed by

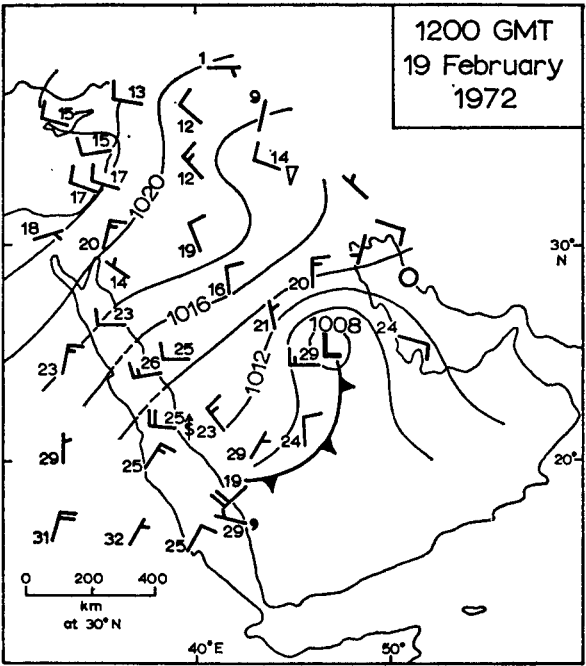


FIGURE 5—SURFACE CHART FOR 12 GMT ON 19 FEBRUARY 1972
Symbols show weather at 12 GMT or during the previous six hours.

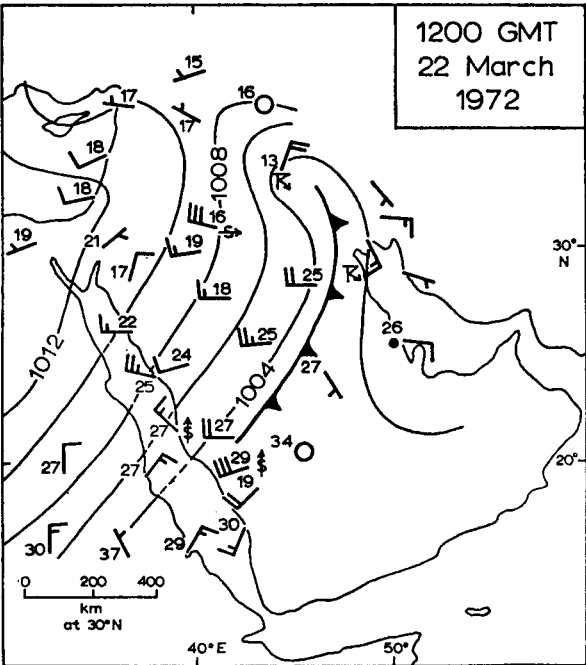


FIGURE 6—SURFACE CHART FOR 12 GMT ON 22 MARCH 1972
Symbols show weather at 12 GMT or during the previous six hours.

further night-time lightning. From 1610 to 1830 GMT on the 22nd there was a thunderstorm with hail and a squall, and rainfall totalled 50 mm. A sudden fall of temperature from 23° to 16°C occurred. It is not possible to say if this storm formed on or somewhat ahead of the cold front. The lower tropospheric moisture probably came from the south-west, i.e. the Red Sea, but some may have come from the south-east, i.e. the Arabian Sea, judging by dew-points above 10°C at Sulayil.

As pressure built quickly to the north, an anticyclone (central pressure 1014 mb) developed over the north-east of the country by 12 GMT on the 23rd, resulting in north-east winds in the east and south-east winds in the west. As a result, the front accelerated eastwards across the Persian Gulf, although south-west winds persisted in the south-west, and moist air continued to flow over Riyadh from the Persian Gulf, even reaching Qassim on the 24th.

This interesting disturbance was accompanied by strong south-west winds in the middle and upper troposphere (Figure 7), but the greatest changes in direction were again below 700 mb. A large-amplitude trough was slow moving near 35°E from the 21st to 23rd, giving persistent south-west upper winds over the whole of Saudi Arabia. At 200 mb, the axis of the subtropical jet stream formed a sinusoidal pattern: a ridge over Algeria (27°N 6°E), a trough over Egypt (22°N 35°E) and a ridge over central Asia (41°N 70°E). Thus, Riyadh lay close to the southern side of the axis, and to the east of a stationary trough, i.e. in a region where strong upper divergence is to be expected. This divergence, together with a combination of surface heating and a lower tropospheric inflow of moist air, seems to have resulted in deep convection and the development of a severe storm at Riyadh. The synoptic pattern was similar to those where the subtropical jet stream is associated with severe storms elsewhere in the world. Moreover, thunderstorms were also reported in Mauritania on the 22nd in a similar situation, but ahead of the upstream trough — also slow-moving — off the north-west coast of Africa.

1 May 1972. A well-marked cold front moved south-east across Riyadh at 1225 GMT, with a temperature fall from 36° to 30°C between 12 and 13 GMT,

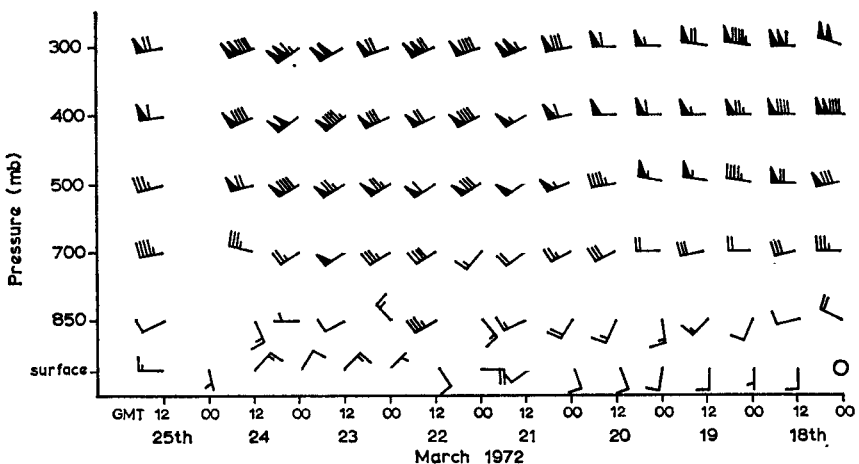


FIGURE 7—VERTICAL TIME-SECTION SHOWING WINDS AT RIYADH, 18–25 MARCH 1972

accompanied by a short spell of blowing dust as the wind veered from west-south-west to west-north-west. This front had crossed Tabouk on the night of the 29th/30th, Hail between 16 and 17 GMT on the 30th, and Qassim between 03 and 04 GMT on the 1st. By then there was some evidence for the formation of a new low-pressure centre, which moved east-south-east at about 20 kt to cross Dhahran at 22 GMT. Prefrontal south-west winds at Riyadh brought dew-points of 12–14°C from the Red Sea, accompanied by cumulonimbus clouds but no rain, although there was lightning in the evening. Dew-points rose to 15–17°C behind the front, probably as a result of advection around the north side of the developing depression, but they fell towards 0°C early on the 2nd.

The front was associated with a deep depression over the eastern Mediterranean. On the 29th, the front was lying from Jordan to south-eastern Egypt (Figure 8); ahead of it south to south-east winds covered most of Saudi Arabia with duststorms in the northwest, where moist air from the Red Sea brought dew-points around 10°C and widespread cumulonimbus, which was also present over high ground in the south-west. Surface north-west winds behind the front pushed along the length of the Red Sea, reaching south of Jizan on the 1st (Figure 9). This vigorous cold front was associated with a cyclone at 500 mb that moved from the eastern Mediterranean on the 29th to the Black Sea on the 2nd, with its accompanying trough in the westerlies crossing Riyadh late on the 2nd, i.e. nearly a day and a half after the surface front. Temperatures fell by 10 degC in 24 hours at 850 mb, but 5 degC at 700 mb and less at higher levels.

29 May 1972. A cold front moved south-eastwards across Riyadh between 09 and 10 GMT, when the wind veered from south to west-north-west and decreased in speed. Dew-points rose from 0°C to about 8°C, but temperature changes were little different from those expected in a diurnal variation. The front had passed Hail between 11 and 12 GMT on the 27th, and Qassim between 19 and 20 GMT on the same day, by which time there was again some evidence for the formation of a new low-pressure centre, moving east at 10 kt, reaching Dhahran by 18 GMT on the 29th. At Dhahran the temperature reached as high as 47°C at 12 GMT (Figure 10), when the wind direction was off shore. Only small cumulus clouds formed near the centre of this depression, but again there was cumulonimbus over the mountains of the south-west.

A short-wave trough at 500 mb moved eastwards across Riyadh early on the 30th but weakened as another trough developed over Egypt in association with a slow-moving cyclone over south-west Turkey. A temperature fall of 5 degC occurred at 850 mb, but changes were small at higher levels.

Conclusions. These few examples show that surface pressure troughs, with associated changes of wind from generally south-east to north-west, cross Riyadh some one to two days ahead of the axes of eastward-moving troughs in the middle- and upper-tropospheric westerlies. This vertical structure, together with the periodicity of 2–8 days, closely resembles the structure of springtime disturbances over north-east Africa.⁴ Like the latter, the Arabian disturbances are of two principal types:

- (a) cold fronts that have moved into the country from further west;
- (b) small cyclonic circulations that form over the north-west of the country, subsequently moving east or south-east at 5–15° longitude per day.

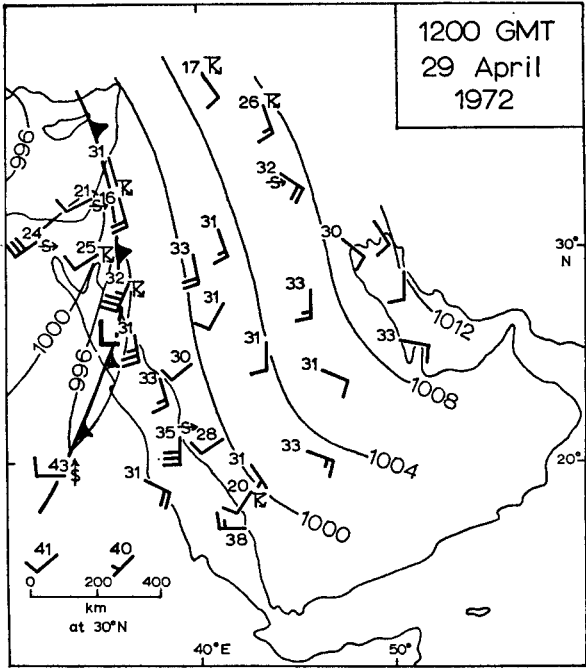


FIGURE 8—SURFACE CHART FOR 12 GMT ON 29 APRIL 1972
Symbols show weather at 12 GMT or during the previous six hours.

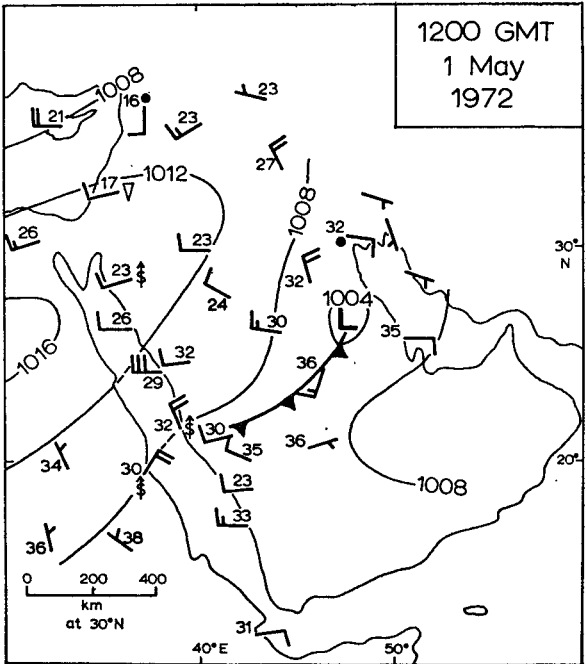


FIGURE 9—SURFACE CHART FOR 12 GMT ON 1 MAY 1972
Symbols show weather at 12 GMT or during the previous six hours.

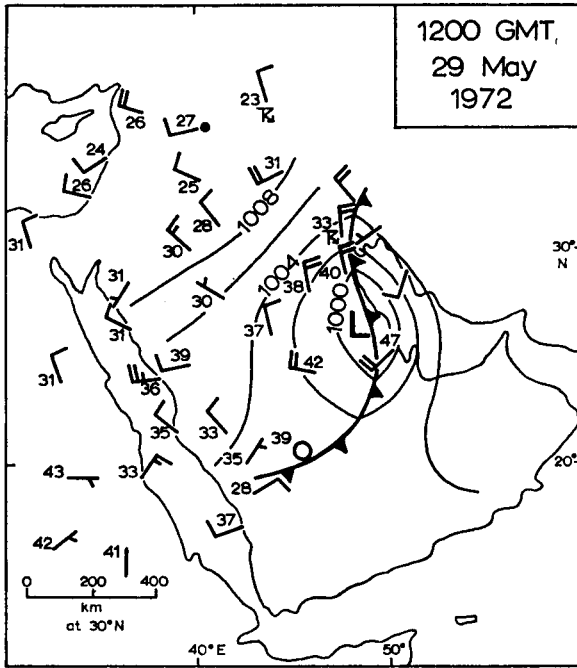


FIGURE 10—SURFACE CHART FOR 12 GMT ON 29 MAY 1972

Symbols show weather at 12 GMT or during the previous six hours.

The cyclonic circulations can develop either on a cold front or independently, within a south-easterly airstream on the western side of a retreating surface ridge. In the latter situation a cold front tends to develop along the axis of the pressure trough after about a day's travel across the centre of the country. The reasons for a preferred origin over north-western Saudi Arabia can only be guessed at, but this is a region where the lower tropospheric thermal pattern frequently has a warm ridge, presumably because the otherwise undisturbed easterly winds (with a south-north temperature gradient) are topographically distorted to south-east (on the north-east side of the massive highland complex of south-west Arabia and Ethiopia) and to north-east (on the north-west side of the highlands). When upper divergence develops temporarily, e.g. ahead of an advancing trough in the westerlies, and especially on the south side of the subtropical jet-stream axis to the east of where it crosses the trough line, the accompanying surface convergence can be expected to distort further the lower tropospheric wind and temperature fields so that a cyclonic circulation develops. As a centre moves away eastwards it will not develop much because it enters a region where the lower tropospheric temperature field is less favourable. The subsequent fate of these disturbances has not been examined.

Upper tropospheric divergence can also be related to the occurrence of middle- and high-level clouds, sometimes extensive and with occasional rain. Cumulus clouds develop where there is a sufficiently moist inflow in the lower troposphere, either:

- (a) ahead of the cold front, from the south-east (Arabian Sea or Persian Gulf) or especially from the south-west (Red Sea); or

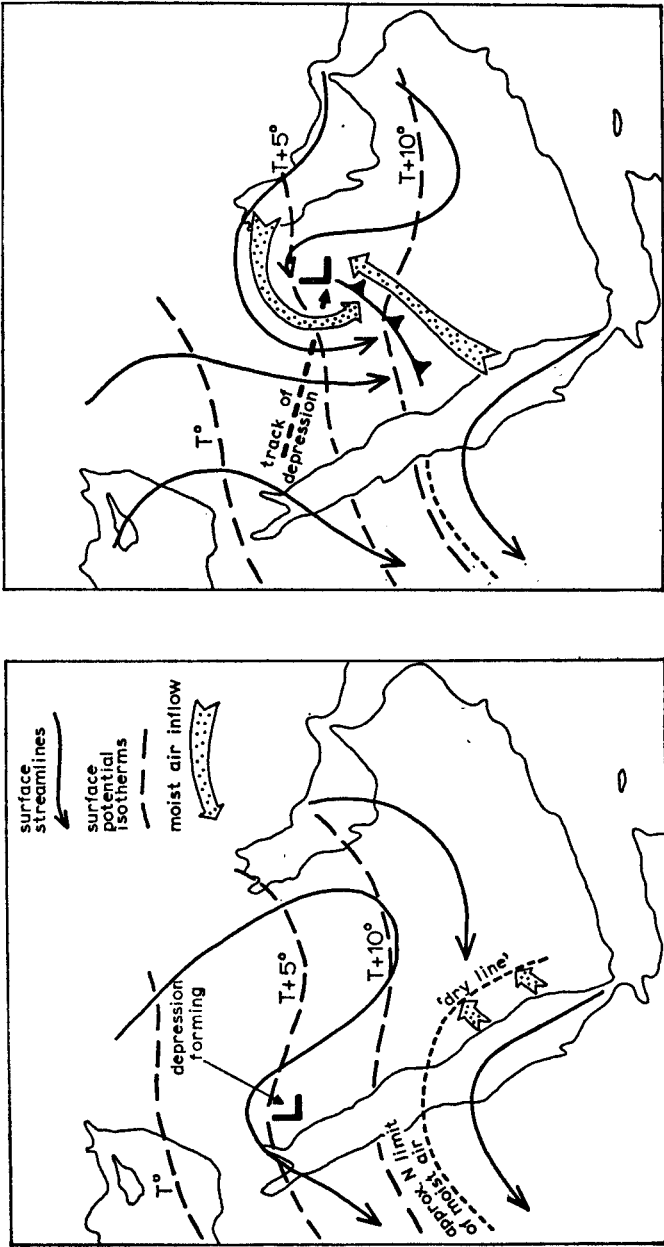


FIGURE 11—SCHEMATIC REPRESENTATION OF WIND AND ISOTHERM PATTERNS IN A DEPRESSION FORMING OVER NORTH-WESTERN SAUDI ARABIA AND MOVING EASTWARDS, SHOWING INFLOW OF MOIST AIR CONDUCTIVE TO THE DEVELOPMENT OF CONVECTIVE LOW CLOUDS

- (b) behind the cold front, from the north-east (i.e. from the Persian Gulf after passing around the northern side of the depression).

Southerly winds are frequently present over the southern Red Sea from October to May,⁶ especially at 850 mb where they spill over the south-western plateau (e.g. at Khamis Mushayt) and are strongly contrasted with the usually much drier north-east to south-east winds of the interior (e.g. at Bishah and Sulayil). A 'dry line' can be visualized as being a quasi-permanent feature of this region. The southerlies are a source of moisture which can occasionally be drawn north-eastwards ahead of a cold front; on other days the moist southerlies appear to turn through east as they leave the Red Sea to flow south-westwards across the Sudan. These developments are shown schematically in Figure 11.

Acknowledgements. The research reported in this paper would not have been possible without the generous provision of data from original observation registers maintained by the Directorate-General of Meteorology in Jiddah, Saudi Arabia. The paper is presented with the permission of the Director, Centre for Overseas Pest Research, London.

REFERENCES

1. KUO, W. S.; A study of weather over the Arabian peninsula. *Met Bull, Taiwan Weath Bur, Taipei*, **11**, 1965, pp. 25-35 (translation available in the Meteorological Office Library, Bracknell).
2. MURRAY, R. and COULTHARD, G. A.; A thunderstorm at Sharjah, Persian Gulf, on 23 November 1957. *Met Mag, London*, **89**, 1959, pp. 176-178.
3. PEDGLEY, D. E.; A heavy rainstorm over north-western Arabia. Boston, Mass., American Meteorological Society and World Meteorological Organization, Proceedings of the Symposium on Tropical Meteorology, June 2-11, 1970, University of Hawaii, Honolulu, 1970, p. E VII 1.
4. PEDGLEY, D. E.; Desert depressions over north-east Africa. *Met Mag, London*, **101**, 1972, pp. 228-244.
5. PEDGLEY, D. E.; The Red Sea convergence zone. *Weather, London*, **21**, 1966, pp. 350-358 and 394-406.

REVIEWS

Theory and applications of numerical analyses, by G. M. Phillips and P. J. Taylor, 225 mm × 150 mm, pp. x + 380, *illus.*, Academic Press Inc. (London) Ltd, 24-28 Oval Road, London, NW1 7DX, 1973. Price: £5.80 (hard cover), £3.90 (soft cover).

The authors have written the book as an introductory text on numerical analysis for undergraduate mathematicians, computer scientists, engineers and other scientists. The reviewer is not a professional teacher or lecturer and has studied the book from the point of view of a meteorologist whose particular line of work depends heavily on numerical analysis, and who has frequent recourse to information and instruction from such texts.

The great impetus given to numerical analysis by the advent of electronic computers has resulted in a rapid evolution of the subject. This has been most evident in research papers and has been difficult for textbook writers to keep up with. Nevertheless this book is modern in its approach without being encumbered by too much of the terminology of 'modern algebra'. Indeed the

sentence 'We have included only a little on finite differences as they are not extensively used nowadays and are of little conceptual interest' may be regarded by many meteorologists as futuristic rather than modern.

It deals with the usual topics of interpolation, approximation, numerical differentiation and integration, solution of algebraic equations of one variable, systems of linear equations, systems of non-linear equations, ordinary differential equations, and boundary-value problems. Two notable omissions are sections on partial differential equations and eigenvalues. The omission of partial differential equations from a book of this scope is understandable as it is a very specialized topic. However, eigenvalues and eigenvectors are another matter, as they underlie so many applications, and so many of the difficulties which scientists encounter in the field of numerical analysis can be resolved by throwing the problem under examination into some canonical form, whereupon the nature of the difficulty is illuminated by a study of the eigenvalues of a matrix associated with the problem. An introductory text at this level should not leave its readers unaware of the power of such important tools as eigenvalues and eigenvectors. The topics dealt with are presented clearly and concisely and the text is well laid out, making the book easy to read and understand. In the chapter on 'best' approximation it is true, as stated, that of all the L_p approximations for $1 < p < \infty$ the L_2 norm is the only one commonly used (i.e. least-squares approximation), but this does not justify the very scant treatment of the L_1 norm for approximation, especially in view of the very large volume of work on this topic over the past two decades and the advantages which the L_1 norm has with respect to erroneous data. It would have been appropriate to give the L_1 norm as much space as has been given to the L_∞ (minimax) approximation. There should also be much more on splines. Splines have been developed into a major interpolation and approximation tool over the past decade and deserve far more than two brief paragraphs. For students, for whom the whole book may be required reading, perhaps the index does not matter too much, but a working scientist will often use a book to try and get information on one specific topic *quickly*. For this a good subject index is needed. Most publishers seem to fail their customers here. A case in point with this book is that the sole reference to the L_1 approximation is given in the index as being on page 83. It is there all right, but another important property of the best L_1 approximation turns up on page 98. The text is well supplemented with examples for working, hints on solution, and, at the end of the book, the solutions themselves with, where necessary, brief remarks on how the solutions are obtained. Thus a reader should be able to consolidate his grip on the subject matter. The reviewer notes that the notation for problem 8.37 is not consistent with that of the foregoing chapter which follows the more customary usage of allowing the columns of the matrix to run through the domain-space whilst the rows run through the function-space.

To offset the above criticisms the book has two excellent features. First, it is a common experience these days that to reach some slight result in a research paper it is first necessary to wade through three or four pages of set-theoretical jargon in which the authors mainly establish that they have heard of mathematical rigour until finally one alights upon a result which could have been adequately proved on one page. Phillips and Taylor have included a chapter called 'Basic Analysis' which is a glossary of necessary terms with examples to

drive the meanings home. Thus if you are apt to be put off by the statement that a certain theorem is true provided that $f(x)$ satisfies a Lipschitz condition on $[a, b]$, Phillips and Taylor not only tell you what a Lipschitz condition is, they also make sure you understand it. Second, the Chapters 8 and 9 which introduce matrix/vector methods into the study of linear equations and the applications of matrix/vector norms will enrich the subject of numerical analysis for readers not already familiar with the power of this approach. In particular the authors are to be commended for their Chapter 9 which deals with matrix/vector norms, rounding errors, conditioning problems, and iterative methods. The interaction of condition number and round-off error is at the heart of the matter as far as many of the large problems of modern numerical science are concerned and the authors have achieved a clear and succinct account of this area.

Scientists whose work involves numerical analysis have a need for textbooks at various levels to be available for quick reference. At £3.90 this book is good value and is a worthwhile addition to such collections.

R. DIXON

Radiant heat transfer, by E. M. Feigel'son. 250 mm × 175 mm, pp. iv + 191, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £8.60.

It is thought that radiative processes may play a part in the origin of anomalies of the general circulation of the atmosphere that continue for a time-scale of months or years. Understanding these effects and their relationship to climatic variation is therefore a fundamental problem of atmospheric physics. Unfortunately many meteorologists find difficulty in understanding the physics of radiative transfer and when faced with introducing their effects into atmospheric models resort to empirical relationships of dubious origin. Professor Feigel'son's book is an attempt to unravel some of the mysteries of radiative transfer in a cloudy atmosphere and examine the validity of some of the approximations that are in vogue. Unfortunately it does not completely succeed. The author's monograph is strictly a text for the specialist. The brief excursions into the realm of general-circulation models and atmospheric dynamics are really a résumé of the state of the art in 1967 when the book was originally written in Russian. There is little discussion of possible improvements to the existing schemes, which indicates that the author has limited experience in this area. A further limitation of the book concerns the neglect of the solar characteristics of cloudy atmospheres. In spite of these deficiencies, the radiative-transfer specialist will find the book an interesting addition to the subject.

An introductory chapter briefly surveys the properties of clouds in terms of their altitude and radiative properties. As usual almost all the discussion is concerned with water-droplet clouds, which emphasizes that we still need detailed information on the radiative properties of ice clouds. The second chapter provides a limited discussion on the instrumentation used to produce the radiative observations discussed in later portions of the book. The main portion of the book is concerned with methods for computing the infra-red energy and surveys the standard methods for clear atmospheres. Techniques for

cloudy atmospheres are also considered. The author is critical of the manner in which radiation and clouds are introduced into general circulation models, but provides little in the way of possible improvements.

The final chapters describe numerical experiments which investigate the effects of radiative heat exchange on the development of cloudiness.

The book reflects the scientific interests of the author and does not claim to be a comprehensive description of the subject. The translation of the original Russian text has been carefully edited and the only criticism of the printing concerns the diagrams which are sometimes too small to read all the information they contain. In spite of the limitations stated earlier, the book is a useful addition to the subject which will interest specialists in atmospheric radiative-transfer theory.

G. E. HUNT

Airflow over mountains—research 1958–72, WMO *Technical Note* No. 127, by J. M. Nicholls. 280 mm × 215 mm, pp. xii + 74, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1973. Price: Sw. Fr. 27.

Technical Note No. 34 with the same title covered the years up to 1958. Much has been done since then because of increased flying in the stratosphere. Earlier theories did not have very specific predictions about what took place above the tropopause because there can be so many different kinds of behaviour. With more observations the theories are in a better position to give more understanding.

Mr Nicholls has performed a very valuable task in helping the coming generation of researchers. He was at a disadvantage in having to be fair to everyone, especially since much work is still going on and is developing quite rapidly, particularly to deal with unsteadiness of the flow and three-dimensional aspects. A reviewer can risk being unfair and if this can stimulate interest in the subject through Mr Nicholls's *Technical Note* it will be worth while.

The weather is, as every meteorologist knows, dramatic, and the more we know about it the more dramatic it becomes. One is therefore not impressed by artificial drama of the 'plane (travelling at 200 m.p.h.) is hit by tornado (travelling at 15 m.p.h.)' kind. Thus, on reading 'Suddenly, and without any warning at all, the indicated air speed dropped in under one second from about 198 kt to 150 kt at 47,300 ft . . .', followed by a statement that it 'was literally staggering; I failed to operate the fast recorder or even speak into the tape recorder', one is led to suspect that the intrepid aviator had thought of himself as the driver of a bus load of instruments, so far was he removed from the thinking shop in this research.

The whole object of the exercise was, of course, to find out about unknown phenomena, and research is very inefficient if communication between components is inadequate. At the other end, where high-powered theoreticians set bright young students to work, there is far too much clever mathematics, which gets published all right, but does not get through to the man in the air because it doesn't try to. If it did try, it would concern itself less with more complicated solutions of simple situations and more with simple approaches to

complicated situations — which is what exist out there in nature. Many of the mathematical issues that are brilliantly handled arise because of the model chosen, and fade away when the crude realities of three-dimensional unsteady flow intrude. People have gone to quite absurd lengths to obtain more accurate two-dimensional solutions for uniformly stratified airstreams or highly computerized steady two-dimensional solutions in which a rigid lid is placed on the model and several parameters disposed in such a way as to produce something like one of the main features observed in a highly unsteady case over ragged mountains.

But one is never more conscious than in this field of the inability of people to be original. Our thinking jogs along behind our experience, and if that experience is mathematical or hydraulic it comes out in the kind of theory one uses. 'Are you interested in infinite series?' said one well-known author in this field to me during an international conference visit, as we looked up at a magnificent wave cloud, with billows streaming through it: I was embarrassed by my speechlessness.

There is the school that uses 2D vortices, or doublets, or ridges of elliptical cross-section, and obtains the answer far more correctly than ever before, or finds waves from a hemispherical mountain in a uniform stream which would be completely obscured by a host of other waves in a non-uniform one over any shape of mountain. There are those who see hydraulic jumps, with which they feel at home, in streams for which there is not even a pretence of a theory for such phenomena, because they do not understand vorticity in a stratified medium. As for 'critical levels', I feel that a great nonsense has been made out of the blowing up of terms in familiar equations applied out of context. More heresy is needed here. Likewise much has been made of the Richardson number, or rather of efforts to find the imagined universal critical value of it at which shear layers become unstable. This is really quite a trivial problem, for most of the time the Richardson number is either above or below the critical value, and we can never hope in practice to catch it just passing through and about to give rise to instability. What we are concerned with is the mechanisms which cause it to change from a large to a small or negative value, and these abound in waves. I was disappointed to see Mr Nicholls quote a relevant sentence of mine about accelerated airflows out of context because a much more important statement occurred in the previous paragraph of the reference he quotes, viz. 'Therefore, rather unexpectedly perhaps, the most stable layers develop the smallest Richardson number in waves, and so billows are most likely to develop here'. Horizontal acceleration or deceleration of the flow in waves is not a significant destabilizing mechanism, although several authors have fallaciously argued that it is.

It is important that this review should end on a congratulatory note because Mr Nicholls himself has probably done more than most people in recent years to bridge the gap between aviator and theoretician, and any fruit that comes from his efforts will be well deserved. He can be assured that at least one group working on waves is very appreciative.

R. S. SCORER.

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NOTICES

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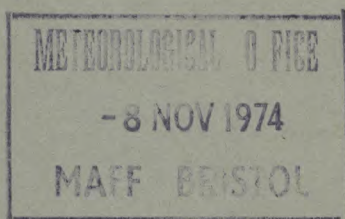
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A SCHEME FOR DERIVING DAY-TIME BOUNDARY-LAYER WIND PROFILES

551-554

By F. B. SMITH and D. J. CARSON

Summary. This scheme for deriving day-time boundary-layer wind profiles uses readily available parameters, namely: time of day, month, cloud amount, surface geostrophic wind and surface wind. The scheme allows for the effects of surface roughness, stability and diurnal and seasonal variations in boundary-layer depth. Typical profiles for both rural and urban sites are derived.

The scheme is illustrated fully by example in the section on 'Application', which may be read independently of the theoretical background which is outlined in the previous section. An extension of the basic scheme to allow for thermal-wind effects is described.

Introduction. This paper describes a scheme for estimating the mean wind-speed profile in a day-time atmospheric boundary layer in terms of the following parameters: time of day, month, cloud amount, the surface geostrophic wind speed and the mean 10-metre wind speed measured by a properly exposed anemometer. At times it may be necessary to replace the surface geostrophic wind by the gradient wind if the air trajectories have significant curvature or to adjust its value to allow for thermal wind effects which, on occasions, can be very important throughout the boundary layer.

The scheme takes account of boundary-layer stability and surface roughness in determining the nature of the wind profile in the lowest few tens of metres and also allows for diurnal and seasonal variations in the depth of the boundary layer which affect the way in which the wind speed approaches the 'free-stream' value (the geostrophic- or gradient-wind value) at the top of the boundary layer.

Two categories of profile are illustrated according to the surface roughness of the terrain over which the profile is to be estimated. One may be classed as a rural profile at the site of the anemometer set within typical English countryside (i.e. above a well-maintained level grass surface surrounded at a reasonable distance by hedges, trees, villages etc.); the other is for use over an urban or forested area.

The second section gives the theoretical background to the basic scheme with reference to source material. The third section gives the procedure for applying the scheme and indicates its limitations. A worked example is also given and this section can be read without reference to the other sections. A further section describes how the thermal wind can be incorporated into the scheme when it is important.

Theoretical background

Parameters needed to specify the profiles. Straightforward formulations of the wind profile throughout the whole of the boundary layer do not exist. The composite profiles presented here are obtained from a combination of the wind profile based on standard similarity-theory arguments applying well below the top of the boundary layer, the height of the boundary layer and the magnitude of the 'free-stream' wind at the top.

The parameters needed to specify the whole profile are:

- (a) z_0 , the surface roughness. The effective z_0 generally varies from one part of the wind profile to another. For the near-surface profile the very local nature of the surface (e.g. short grass) at the site is important but away from the ground z_0 represents an average roughness over an upwind area which is significantly affecting the wind profile at the height concerned. Since at greater heights the effective z_0 will have to take into account hedges, copses, buildings etc. it will generally be greater than the z_0 used closer to the ground.

Four values of z_0 have been used to determine the final composite profiles. At the rural site, assumed to be a typical meteorological observing station, z_0 is assumed 3 cm close to the surface, $z_0 = 10$ cm in a layer containing the anemometer at 10 metres and $z_0 = 30$ cm above about 100 metres, as a typical z_0 for varied English countryside. For the urban profile, which is only applicable at heights well above the height of the roughness elements themselves, $z_0 = 1$ m is taken from about 20 metres merging once more into the profiles for $z_0 = 30$ cm at heights in excess of 100 metres where the urban environment will no longer significantly affect the profile unless the city extends for more than a few kilometres upwind.

- (b) Some measure of the degree of instability in the surface stress layer.
- (c) The total incoming short-wave radiation, R .
- (d) The depth, h , of the atmospheric boundary layer.
- (e) The value of the 10-metre wind speed, u_{10} , corresponding to a surface roughness $z_0 = 10$ cm or, alternatively, the surface geostrophic wind (V_g) or gradient wind (V_{gr}).

A stability parameter in common use in the surface stress layer is the surface Monin-Obukhov length, L , defined by

$$L = \frac{-u_*^3 \rho c_p T}{gkH}$$

where u_* is the surface friction velocity, ρ is the mean density of the air, c_p is the specific heat of air at constant pressure, T is the mean absolute temperature of the air, g is the acceleration due to gravity, k is the von Kármán constant and H is the surface sensible heat flux which is assumed closely related to the incoming solar radiation, R . From his model for boundary-layer profiles in unstable conditions, Smith¹ produced curves of u_z/V_g as a function of the surface Rossby number, V_g/fz_0 (where f is the Coriolis parameter), and a stability parameter, H/V_g^2 . Also, knowing u_z/u_* as a function of z , L and z_0 for the surface layers, Smith provided curves showing the interrelationships between R , V_g , u_* , L , $u_{10}(z_0)$ and z_0 . By use of these relationships it is found that the parameter $V_g/u_{10}(z_0)$ can be represented, to a high degree of approximation, as a function of z_0 and L only and can therefore be used as a stability

parameter in place of L , for any given z_0 . For $z_0 = 10$ cm, $V_g/u_{10} = 2.0$ corresponds, in the absence of thermal-wind effects, to neutral stability, 1.75 to $L \approx -100$ m and 1.5 to $L \approx -10$ m.

A further result from Smith's curves is that the wind speed $u_{10}(z_0)$ at 10 metres corresponding to a surface roughness z_0 is proportional to the wind speed u_{10} at 10 metres corresponding to a surface roughness of 10 cm, under the same external conditions of R and V_g . The constant of proportionality is, to a good approximation, independent of the Monin-Obukhov length, L . In particular:

$$\frac{u_{10}(z_0)}{u_{10}} \approx r(z_0) = \begin{cases} 0.86 & \text{for } z_0 = 0.3 \text{ m,} \\ 0.73 & \text{for } z_0 = 1.0 \text{ m.} \end{cases}$$

The new stability parameter $V_g/u_{10}(z_0)$ is therefore readily replaced in the analysis by V_g/u_{10} .

The presentation of the profiles is greatly simplified by these observations and the format

$$\frac{u_z}{u_{10}} = f(z, z_0, V_g/u_{10}, h)$$

is adopted, where z_0 is a function of height reflecting the upwind variations in surface roughness, as discussed above.

Determination of the stability parameter V_g/u_{10} . In some situations both u_{10} and V_g will be known from anemometer readings and synoptic charts. The stability parameter V_g/u_{10} will then be known directly. In areas of complex topography this may be the only acceptable way of proceeding. Otherwise one or other of u_{10} and V_g must be available and can be used together with the incoming solar radiation, R , to deduce the stability parameter. However, R is not generally readily available but can be estimated from three easily assessed parameters, namely the time of day, the month and the cloud amount. Figures 1 and 2, based on four years of radiation data from Cambridge, show the dependence of R on the three parameters. A value of R for 0-1 oktas of cloud is estimated from Figure 1 and is modified for the actual cloud amount from Figure 2. The derivation of these figures, first used by Smith *et alii*,² is based on information on the Cambridge radiation data discussed and displayed in Smith and Jeffrey.³

Figure 3 represents V_g/u_{10} as a function of R and u_{10} and is derived as a direct consequence of Smith's¹ curves and the inferred relationship between V_g/u_{10} and L . Alternatively V_g/u_{10} can be represented as a function of R and V_g by the directly related Figure 4.

Figures 1, 2 and 3 (or 4) provide then the stability parameter V_g/u_{10} which will be used in the classification of the profiles.

The wind profile in the surface stress layer. The wind profile in the surface stress layer is determined from the Monin-Obukhov similarity theory formulation,

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz} \varphi_m(z/L),$$

where, following Businger⁴ and Dyer and Hicks,⁵ $\varphi_m(z/L)$ for neutral and unstable conditions is given by

$$\varphi_m(z/L) = (1 - 16 z/L)^{-1/4}, \quad |z/L| \leq 1.$$

After integration this gives

$$\frac{u_z}{u_{10}(z_0)} = \frac{\chi(\xi_z) - \chi(\xi_{z,0})}{\chi(\xi_{10}) - \chi(\xi_{z,0})}$$

$$\approx \frac{u_z}{r(z_0)u_{10}},$$

where

$$\chi(\xi_z) = \ln \left[\frac{\xi_z - 1}{\xi_z + 1} \right] + 2 \tan^{-1} \xi_z$$

and

$$\xi_z = (1 - 16 z/L)^{\frac{1}{2}}.$$

The low-level profiles were determined in this way with V_g/u_{10} used as the stability parameter for classification purposes.

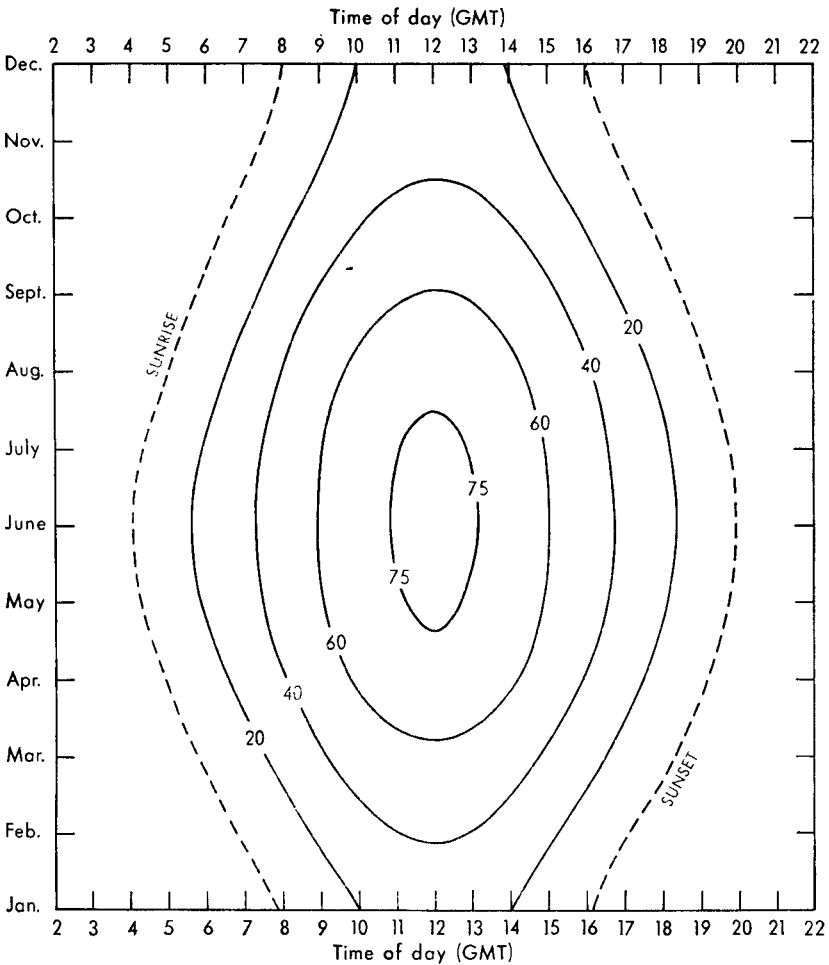


FIGURE 1—INCOMING SOLAR RADIATION, R_0 , IN MILLIWATTS PER SQUARE CENTIMETRE FOR 0-1 OKTA OF CLOUD

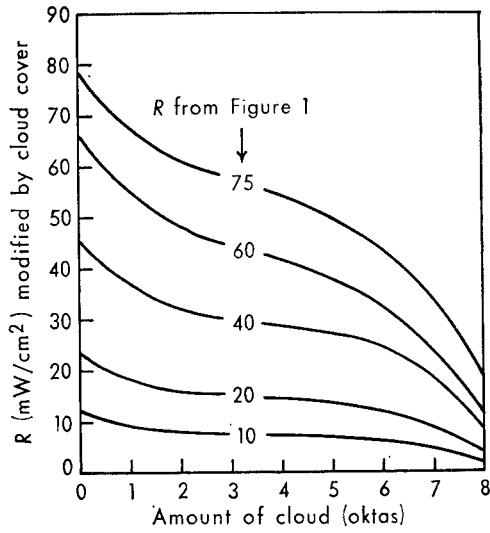


FIGURE 2—INCOMING SOLAR RADIATION MODIFIED BY CLOUD COVER
As deduced from unmodified value R_0 from Figure 1.

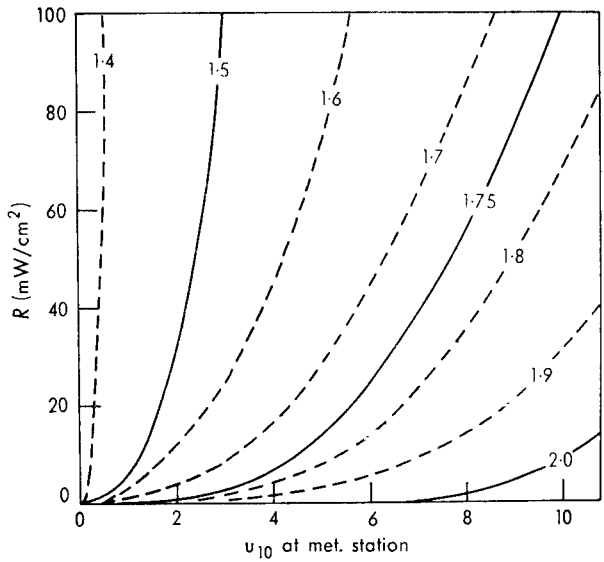


FIGURE 3—CONTOURS OF V_g/u_{10} IN TERMS OF R AND u_{10}
Values of u_{10} are in metres per second.

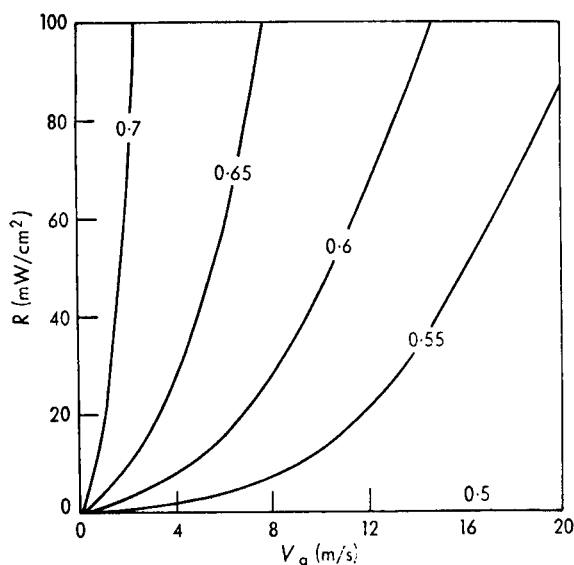


FIGURE 4—CONTOURS OF u_{10}/R IN TERMS OF R AND V_g

The wind profile above the surface stress layer. To determine the wind profile from the top of the surface stress layer to the top of the boundary layer we use the two parameters V_g/u_{10} and h and assume that the wind speed will attain the 'free-stream' value V_g at $z = h$.

The value V_g/u_{10} is obtained either directly or by the procedure described above.

To obtain a reliable estimate of h is not an easy task. There are, generally speaking, no estimates of this depth readily available, although radiosonde ascents might be used with caution to provide an estimate at certain times. It should be noted that formulae based on the steady-state similarity approach applied to the whole layer are only of use for estimating h if the boundary layer is neutral and has been so for some time. Such formulae are quite inadequate for use with the generally non-steady, diabatic boundary layer. This is because the depth is determined by mechanical mixing and the total amount of heat which has entered the layer, not just the heat received at any instant.

The determination of h , in the absence of any direct information, has been somewhat simplified and reduced to the nomogram of Figure 5. Here h is determined as a function of time of day, month, cloud amount and the wind speed at 10 metres at the meteorological station site (i.e. 10 cm is the effective surface roughness for the profile at 10 m). The curves are based on the developing boundary-layer model of Carson⁶ which has been used with mean boundary-layer temperature profiles obtained by Hardy (private communication) from a study of Balthum ascents at Cardington over a period of 10 years. This type of approach was first developed for a practical scheme, designed and discussed by Smith,⁷ for estimating the vertical dispersion of a plume from a source near ground-level. Here we have extended the basic model to allow for a contribution to h due to mechanically, as opposed to thermally, generated turbulent mixing.

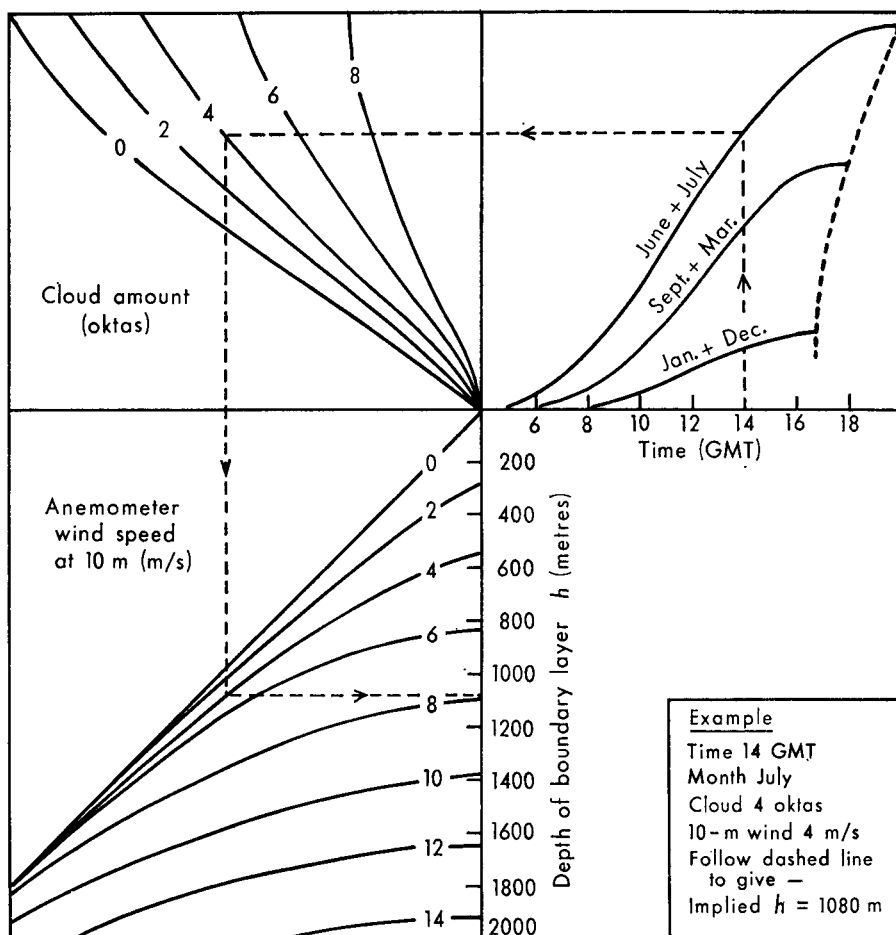


FIGURE 5—NOMOGRAM FOR THE DETERMINATION OF THE DEPTH OF THE BOUNDARY LAYER, h

Knowing the height h at which u_z/u_{10} attains the derived value V_g/u_{10} it is necessary to carry a somewhat subjective extrapolation of the low-level profile for $z_0 = 30$ cm to meet this upper-boundary condition.

Finally a matching process has to take place between the profiles for the three values of z_0 . The profile for $z_0 = 3$ cm is given most weight in the first few metres, appropriate to the surrounding grass-covered area. At 10 metres the actual anemometer wind, u_{10} , gives a fixed point and account is taken of the slope of the profile there corresponding to $z_0 = 10$ cm. Above about 100 metres the composed profile for $z_0 = 30$ cm described in the previous paragraph is given greatest weight, appropriate to the effect of distant, more severe, roughness. Naturally there is a further element of subjectivity in this matching process but with so many fixed constraints (the value of z_0 at the ground, u_{10} , h etc.) the expected errors arising from this are really quite small.

Over an urban area the matching process blends the profile for $z_0 = 1$ m below 100 metres into the derived profile for $z_0 = 30$ cm above about 100 metres. Note that the urban profile cannot have meaning below about twice the typical building height.

These profiles are presented in Figure 6 for several values of V_g/u_{10} and h .

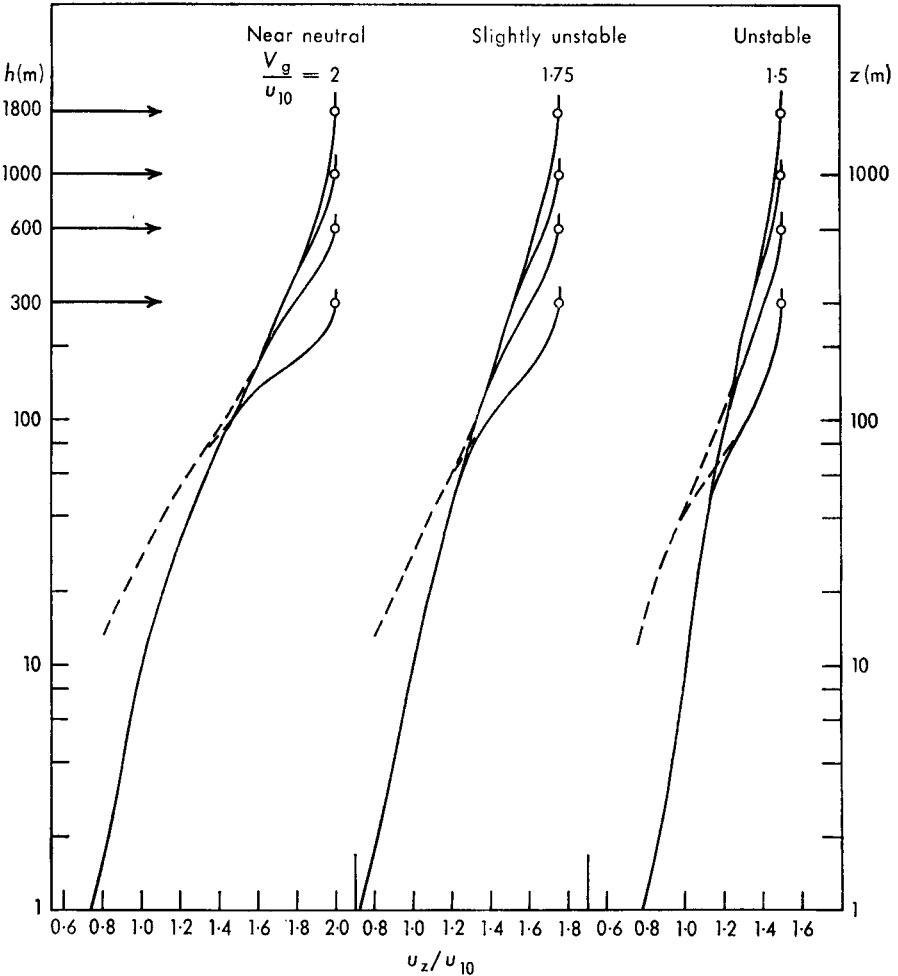


FIGURE 6—EXAMPLES OF WIND PROFILES

Below 100 metres pecked lines denote urban profile and continuous lines the profile at meteorological stations.

The application of the scheme. This section describes how to use the scheme without reference to the theoretical background given above. To clarify the process an actual example will be followed step by step; the example assumes the following conditions:

- (a) Time: 14 GMT; month: July; place: a typical meteorological observing station in central England, set in the country.

- (b) Cloud amount has been fairly steady through the morning and midday period at 4 oktas.
- (c) Average wind speed at 10 metres (height of anemometer) is 4 m/s.

Step 1. Estimate the incoming solar radiation R .

From Figure 1 read off R_0 appropriate to 0–1 oktas cloud for the month and time of day.

In the example $R_0 \approx 68 \text{ mW/cm}^2$ for July, $T = 14 \text{ GMT}$.

Modify R_0 according to the cloud amount, using Figure 2, to give R .

Example: Cloud is 4 oktas, R_0 is 68, which gives R as 48 mW/cm^2 .

Step 2. Estimate the ratio of the geostrophic and 10-metre winds, V_g/u_{10} . If u_{10} is known, then Figure 3 gives V_g/u_{10} in terms of R (found from Step 1) and u_{10} .

If u_{10} is unknown but an estimated value of V_g is obtainable from a synoptic chart, then Figure 4 may be used to give u_{10} and V_g/u_{10} . If both u_{10} and V_g are known directly then this step may be omitted or used simply as a check. Clearly in difficult topographical situations where our scheme may be suspect, direct estimates of V_g and u_{10} may be preferred.

In the example $u_{10} = 4 \text{ m/s}$,

From Figure 3 the value of V_g/u_{10} appropriate to $R = 48$, $u_{10} = 4$ is:

$$\frac{V_g}{u_{10}} \approx 1.6.$$

With significant curvature of the air trajectory, V_g should be replaced by the gradient wind following standard procedures.

Step 3. Estimate the depth of the boundary layer, i.e. where the 'free-stream' wind is first achieved.

If a significant synoptically induced inversion exists, this provides an upper limit to the boundary-layer depth. Figure 5 gives the depth in the absence of any such inversion or when the inversion is higher than that given by the Figure.

Start with the time of day in the top right-hand box; move upwards to meet the appropriate month curve; move left into the top left-hand box to meet the appropriate cloud-amount curve; move down to the bottom left-hand box to meet the u_{10} curve and finally move to the right and read off the estimated value of boundary-layer depth, h . The 'path' taken for the Example is indicated by the dashed line and yields an estimated $h = 1080$ metres.

Step 4. Estimate the wind profile.

To enter Figure 6, the two parameters V_g/u_{10} and h , found above, have to be known.

In the example $\frac{V_g}{u_{10}} = 1.6$ and $h = 1080 \text{ m}$.

The profile has to be interpolated between the curves shown.

In our specific example the profile lies between those given for $V_g/u_{10} = 1.5$ and 1.75 , and following the 'tails' up to $h = 1000 \text{ m}$ (approximately).

The values of u_z/u_{10} which may thus be estimated are shown in Table I.

TABLE I—ESTIMATED VALUES OF u_z/u_{10}

z metres	$V_g/u_{10} = u_z/u_{10}$			u_z^* m/s
	1.5	1.75	1.6*	
1	0.78	0.72	0.76	3.0
10	1	1	1	4.0
40	1.11	1.19	1.14	4.6
100	1.22	1.33	1.27	5.1
200	1.28	1.45	1.35	5.4
500	1.42	1.64	1.52	6.1
1000	1.50	1.75	1.60	6.4

* Appropriate to the example

Step 5. The corresponding wind profile over the city can be inferred using the dashed lines on Figure 6. These should only be taken down to within two building-top heights above ground. Below that wind speeds are very variable and are strongly influenced by individual buildings or arrays of buildings.

In the example the winds at 1 m and 10 m cannot meaningfully be defined. At 40 m the average wind is expected to be 4.1 m/s, which is less than the corresponding rural-site speed by 0.5 m/s. At 100 m and above the speed is hardly affected unless the town extends for more than a few kilometres upwind.

The thermal wind. In previous sections any variation of the geostrophic wind with height through the boundary layer has been neglected. However, in many situations this is not justifiable largely because horizontal temperature gradients result in changes in the horizontal pressure gradient with height.

Four simplified situations may be considered (see Figure 7). Situations (a) and (b) result primarily in a change of geostrophic wind *direction* with height

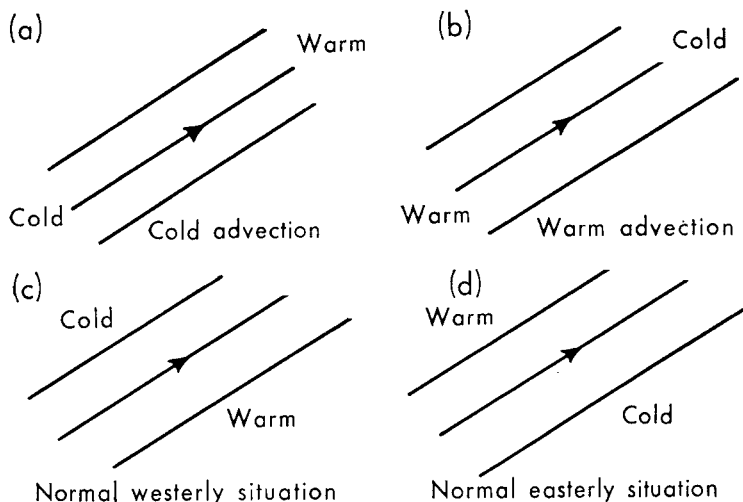


FIGURE 7—THE FOUR SAMPLE SITUATIONS

and we will not concern ourselves with these further. Situation (c) results in an increasing V_g with height whereas in situation (d), V_g decreases with height. The magnitude of these changes is given by

$$\frac{\partial V_g}{\partial z} = -\frac{g}{fT} \left[\frac{\partial T}{\partial y} \right]_p,$$

where strictly $\partial T/\partial y$ is taken normal to the isobars but within a constant pressure surface. Usually this may be approximated by $\partial T/\partial y$ in the *horizontal*, normal to the isobars with an error which is usually well under 1 m/s in $[V_g(z = 1000 \text{ m}) - V_g(z = 0)]$.

Since the difference in V_g between the surface and the top of the boundary layer is of primary importance, a representative $\partial T/\partial y$ appropriate to the whole depth of the boundary layer has to be estimated. Unfortunately screen temperatures (at approximately 1.5 m) are not very representative of the mean temperature in the whole layer. Consequently some adjustment has to be made allowing for heat flux and wind speed and by using the conclusions of similarity theory which give typical temperature profiles as a function of stability and height. These factors are employed to give the potential temperature difference between the screen and $z = 100 \text{ m}$ in terms of R (the incoming solar radiation) and the wind at 10 metres. It will be assumed that the implied temperature at 100 metres yields the required representative temperature of the layer.

Probably an adequate procedure to estimate the thermal wind in the absence of radiosonde data is then to select two well-sited stations lying across wind and one or two hundred kilometres apart, take their screen temperatures, adjust them to 100 metres (using Figure 8) and take the station difference.

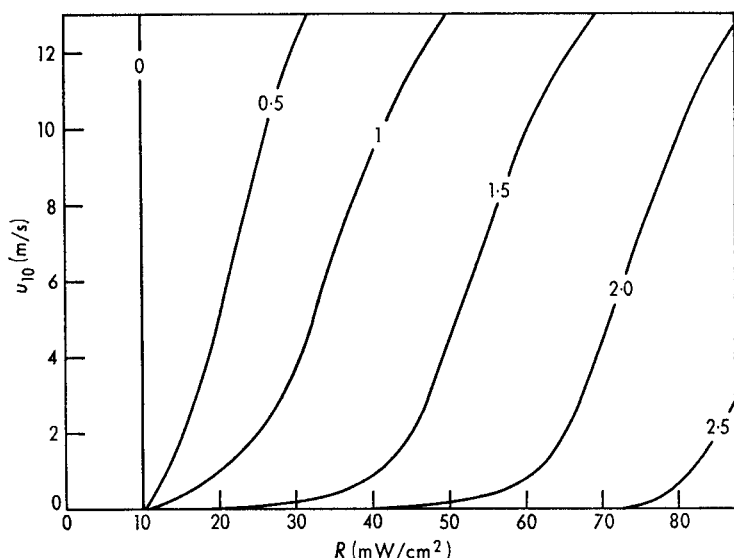


FIGURE 8—CONTOURS OF $\theta(100) - \theta(1.5)$

If we denote the temperatures at the two stations by suffixes A and B, and let the stations be n hundred kilometres apart, then define

$$\Delta_{1000}T \equiv \frac{T_B - T_A + \delta\theta_A - \delta\theta_B}{n},$$

where

$$\delta\theta = \theta(1.5) - \theta(100).$$

The difference in the geostrophic wind between 1000 metres and the surface is then

$$\Delta V_g \approx 3.3 \Delta_{1000}T \text{ in United Kingdom latitudes.}$$

Given that the depth of the mixing layer is not 1000 metres but h metres the change in geostrophic wind speed through the layer is simply

$$\Delta_h V_g = \frac{h}{1000} \cdot \quad \equiv 3.3 \Delta_h T,$$

defining $\Delta_h T$. The magnitude of $\Delta_h T$ is given by Figure 9. The conclusion of this simplified approach is that the magnitude of the geostrophic wind at the top of the mixing layer, h , in terms of u_{10} is given in terms of stability (as in the earlier sections) modified by an additional increment $\Delta_h V_g$,

$$\text{i.e. } V_g(z = h) = V_g(z = 1 \text{ m}) + \Delta_h V_g,$$

remembering that $V_g(z = 1 \text{ m})$ is a function of u_{10} , z_0 and R . The effect of $\Delta_h V_g$ is therefore to modify the ratio V_g/u_{10} used on page 249. Figure 10 shows how this modified ratio can be found very easily. It is immediately obvious that V_g/u_{10} can now lie outside the comparatively narrow range, 1.5 to 2, determined by stability alone.

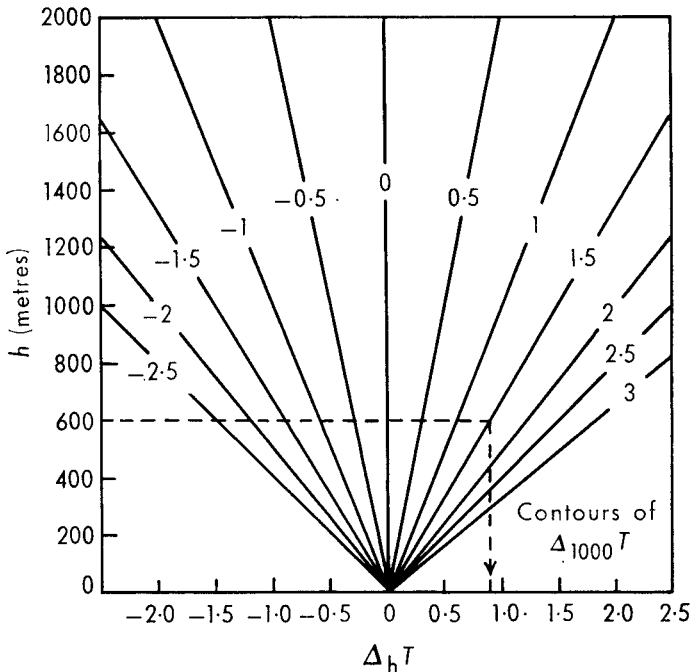


FIGURE 9—DETERMINATION OF $\Delta_h T$

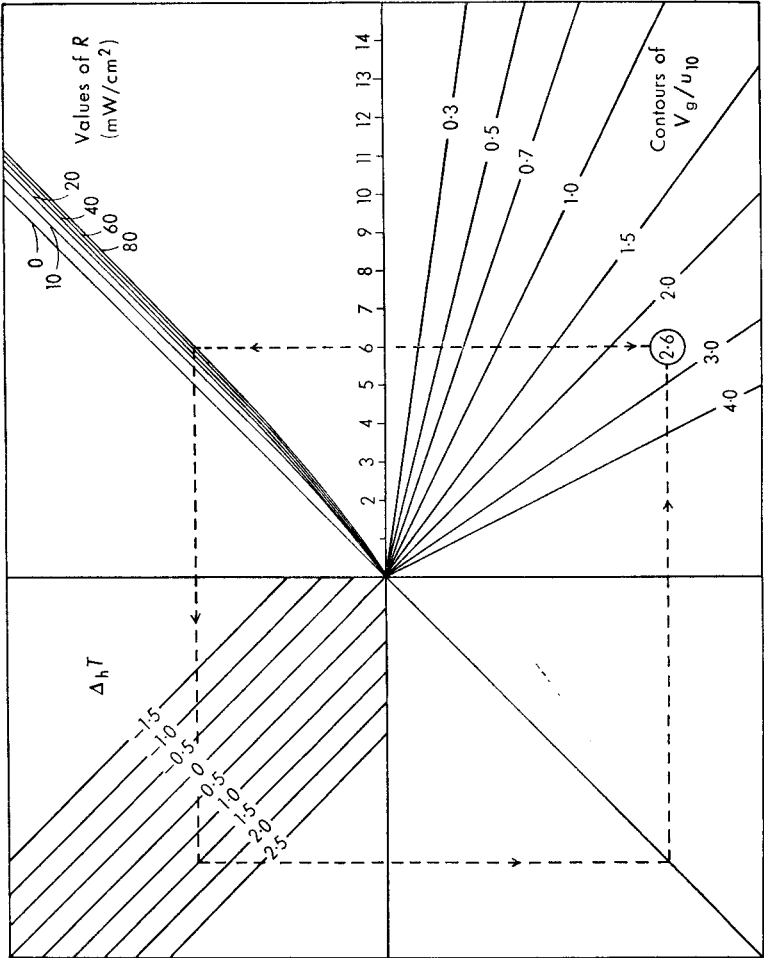


FIGURE 10—NOMOGRAM FOR DETERMINING V_g/u_{10}

Figure 11 shows two sample profiles when the thermal wind effect is quite marked; the one on the left corresponds to an enhanced V_g due to *cold* air to the left of the airstream whilst the one on the right shows a nearly constant wind with height arising from *warm* air to the left of the airstream.

Plotted in this way, profiles are readily constructed. The following constraints and steps may be used:

- $u_z/u_{10} \equiv 1$ at $z = 10$ m.
- At $z = 1$ m over grass $u_1/u_{10} \approx 0.75$ with a gradient which if extrapolated up to $z = 10$ m would give a velocity ratio of 1.4.
- The upper part of the profile is first approximated by a straight line that passes through 0.86 at 10 metres and V_g/u_{10} at $z = 1000$ m. This is then modified by smoothly running from the straight line into V_g/u_{10} at $z = h$, with $\partial u/\partial z = 0$ there, as shown in the several examples.

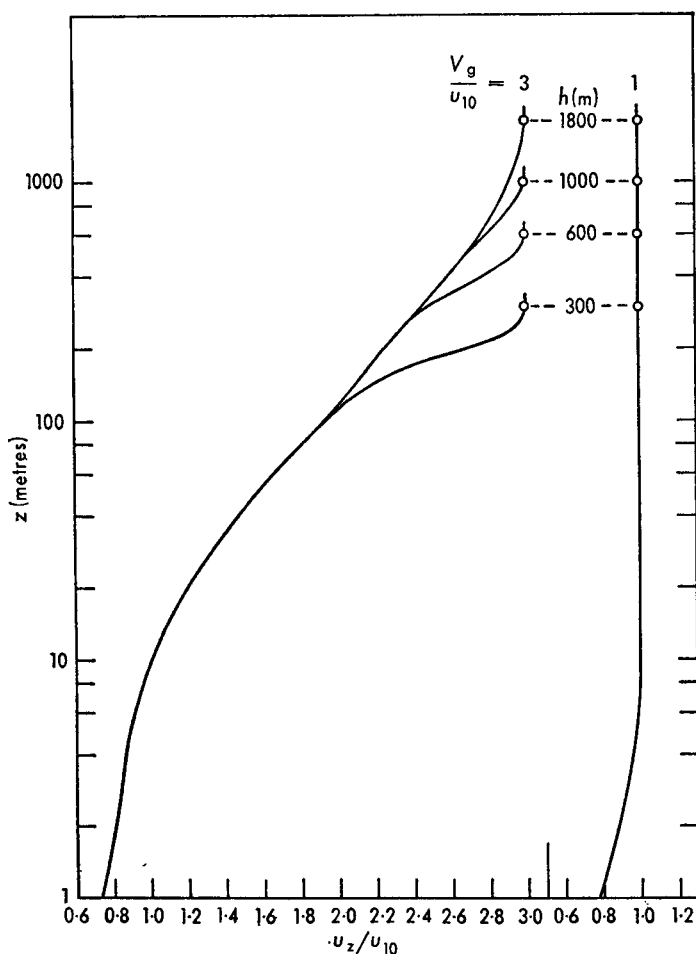


FIGURE 11—TWO EXAMPLES OF WIND PROFILES STRONGLY AFFECTED BY THERMAL WINDS

Both examples are profiles at meteorological stations.

- (d) Finally a smooth profile is constructed linking the parts and subject to all the constraints in (a) to (c).

This rather bold approach must inevitably involve errors, but since the constraints are numerous, these must be relatively quite small. The effect of stability on these 'mixed' profiles therefore must be most pronounced in determining V_g/u_{10} , and the shape otherwise is not seriously affected.

REFERENCES

1. SMITH, F. B.; Boundary layer profiles in unstable conditions. London, Meteorological Office, 1969. (Unpublished, copy available in the Meteorological Office Library, Bracknell).
2. SMITH, F. B., CARSON, D. J. and OLIVER, H. R.; Mean wind-direction shear through a forest canopy. *Boundary Layer Met, Amsterdam*, 3, 1972, pp. 178-190.
3. SMITH, F. B. and JEFFREY, G. H.; The prediction of high concentrations of sulphur dioxide in London air. London, Meteorological Office, 1971. (Unpublished, copy available in the Meteorological Office Library, Bracknell).
4. BUSINGER, J. A.; Transfer of momentum and heat in the planetary boundary layer. Proceedings of a symposium on Arctic heat budget and atmospheric circulation. The Rand Corporation, Santa Monica, California, 1966, pp. 305-332.
5. DYER, A. J. and HICKS, B. B.; Flux-gradient relationships in the constant flux layer. *Q J R Met Soc, London*, 96, 1970, pp. 715-721.
6. CARSON, D. J.; The development of a dry inversion-capped convectively unstable boundary layer. *Q J R Met Soc, London*, 99, 1973, pp. 450-467.
7. SMITH, F. B.; A scheme for estimating the vertical dispersion of a plume from a source near ground level. Brussels, NATO Committee on the Challenges of Modern Society. Proceedings of the Third Meeting of the Expert Panel on Air Pollution Modeling, Paris, Oct. 2-3, 1972, Brussels, 1972, Chap. XVII, pp. 1-14.

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A MEMORABLE RAINFALL EVENT OVER SOUTHERN ENGLAND (PART I)

By PAULINE M. SALTER and C. J. RICHARDS

Summary. During the period 14-16 September 1968 parts of southern England experienced a memorably heavy fall of rain and substantial flooding occurred in places; the rain system was particularly intense over the south-east during the 15th. From a meteorological analysis of the situation it appears that the dominant mechanism governing the precipitation over the south-east was a pronounced convergence zone in the lower troposphere, overlaid at upper levels by a strong positive vorticity advection field operating within a narrow zone of marked horizontal wind shear. This system became slow moving on the 15th and, within it, a low-level inflow of potentially unstable, moisture-laden air is envisaged as leading to the 'dumping' of a heavy fall of rain over a relatively small area.

Introduction. Between 14 and 16 September 1968 parts of southern England experienced an unusually heavy and prolonged rainfall that resulted in extensive flooding in the south-east. Headlines appearing in the national Press on the 16th, following the event, were vivid in their description and may be recalled: 'The Great Deluge—Garden of England is a Paddyfield' (*Daily Mail*), 'Floods Devastate South—Hundreds of homes evacuated' (*Daily Telegraph*), 'September in the Rain' (*Daily Express*). In papers by Bleasdale^{1, 2} this rainfall has been compared with other exceptional rainfall events in the United Kingdom. The purpose of this paper is to describe the sequence of events and the rainfall distribution and, from available data, to offer some explanation for the weather experienced in the light of the meteorological situation prevailing at the time.

Surface analysis and weather sequence. Two rain systems affected southern England during the period 14–16 September and it was the second of these systems that precipitated the memorably heavy fall over south-east England; both systems were associated with a slow-moving depression in the vicinity of the Bay of Biscay. The first rain belt, characterized by vigorous thundery activity, moved northwards across south-west England during the morning of the 14th, reaching the London area by afternoon. The second, and major rain-producing system, developed over northern France and the English Channel during the evening of the 14th and moved slowly north towards the Channel coast of south-east England on the 15th.

Weather over much of the British Isles had been dominated during the first half of the preceding week by a large area of high pressure over Scandinavia. By the 13th a rather slack pressure gradient was covering the U.K. A slow fall in pressure set in over and to the south-west of the British Isles during the 13th and accelerated over the south-west during the evening, and a depression with central pressure of a little under 1000 mb formed off Brest by midnight on the 14th (see Figure 1(a)). Thundery rain and thunderstorms broke out over Brittany and the South West Approaches accompanying this development, and extended slowly north-eastwards over Cornwall and Devon in association with a cold occlusion. A noticeable feature of this system was the vigorous electrical activity associated with it, as registered in the form of atmospheric reports (SFLOCS). During the morning of the 14th the trough moved northwards over southern England, storms on and ahead of the trough triggering off very high repetition rates of SFLOCS in places, and by midday the thundery activity had transferred into the south Midlands, reaching south-east England and East Anglia by afternoon. A clearer, rather unstable south-westerly airflow behind the trough brought drier conditions into extreme southern counties during the morning. During the afternoon the trough became slow moving from the Bristol Channel to the Thames Estuary, and thundery activity started to die out.

The development of the second system was heralded by a general fall in pressure over central France during the afternoon. This extended northwards in the evening, sharpening and rejuvenating the broad trough of low pressure then lying over the English Channel. The surface wind backed and strengthened north-easterly over the British Isles, promoting the development of a marked trough and zone of convergence over the Channel east of Cherbourg later on the 14th (Figure 1(b)). Renewed rain and thunderstorms broke out over France during the afternoon, drifted slowly north over the Channel in the evening and reached Portland Bill and the Isle of Wight shortly after 00 GMT on the 15th. The rain subsequently spread over central southern England and south-east England, south of the Thames. By 06 GMT on the 15th the depression had drifted southwards over Biscay, extending a broad trough north-eastwards over the Cherbourg peninsula and the Dover Straits. The axis of this trough, marking the main convergence zone, transferred slowly northwards over central Kent, and remained slow moving in a north-east to south-west direction during the morning and afternoon, the strong north-easterly airstream to the north of the trough contrasting markedly with the slack southerly flow to the south (Figure 2(a)). Lying south-east of the trough axis, the extreme east of Kent and Sussex escaped the prolonged heavy rain that was affecting places to the north and west. Though thunderstorms were quite extensive within the

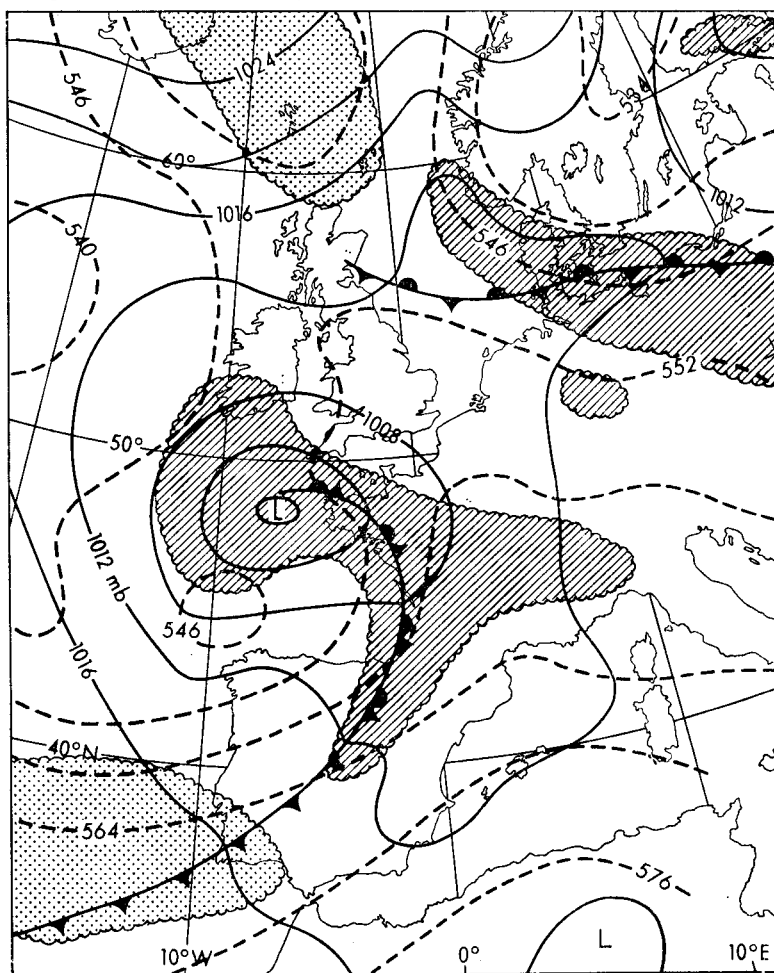
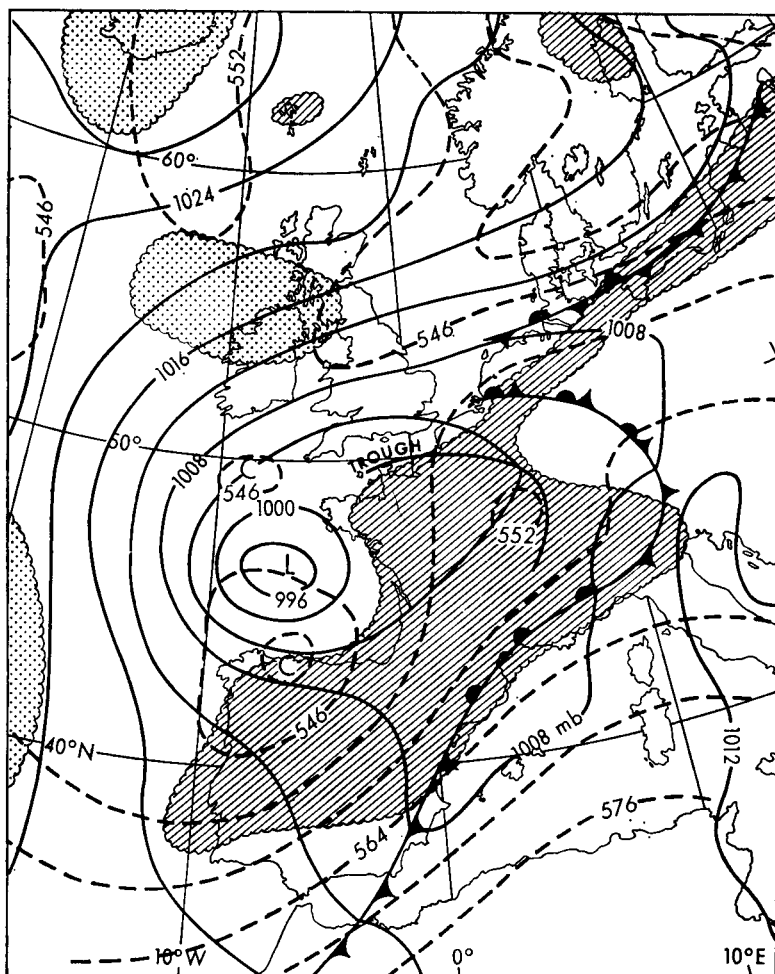


FIGURE 1—SURFACE ANALYSIS AND 1000-500-MILLIBAR THICKNESS, 14-16 SEPTEMBER 1968

(a) 00 GMT, 14 September 1968. Thickness values are in geopotential decametres. Hatching shows wet air at 700 mb (dew-point depression < 2 degC). Stippling shows dry air at 700 mb (dew-point depression > 20 degC).

convergence zone during the morning, the electrical activity (as observed in SFLOC reports) was by no means as intense as it had been over central southern England the previous day.

A temporary improvement was occurring south of the Thames by early afternoon of the 15th, but renewed heavy rain broke out over north Kent, Essex, and Suffolk during the afternoon as a small depression formed within the convergence zone over the Thames Estuary. This depression drifted south-westwards over west Kent, returning heavy rain to parts of Kent and Surrey later in the afternoon (Figure 2(b)), but it disappeared as a separate entity near the south coast during the evening. The rain area extended slowly northwards over East Anglia, precipitating continuous moderate or heavy rain here till 03 GMT on the 16th. It also moved over the south Midlands but rain here was much weaker in

FIGURE 1—*continued*

(b) 00 GMT, 15 September 1968. Thickness values are in geopotential decametres. See also notes under Figure 1 (a)

intensity compared with that nearer the trough. During the evening of the 15th the axis of the trough drifted slowly westwards over the south-east allowing the clearer, drier conditions behind it to spread over Surrey, Kent and Sussex. A further small depression formed in the trough off the Norfolk coast by midnight on the 16th, and drifted over Norfolk, disappearing south of Cambridge by 07 GMT, but at the same time, displacing the main zone of convergence westwards over East Anglia, which it weakened considerably. By midday on the 16th the depression over Biscay had moved over France and degenerated into a shallow, low complex system.

Rainfall distribution. On 14 September rainfall totals in excess of 10 mm were recorded over the area of south-east and central southern England south of a line from Cheltenham to Colchester. The heaviest totals recorded on this

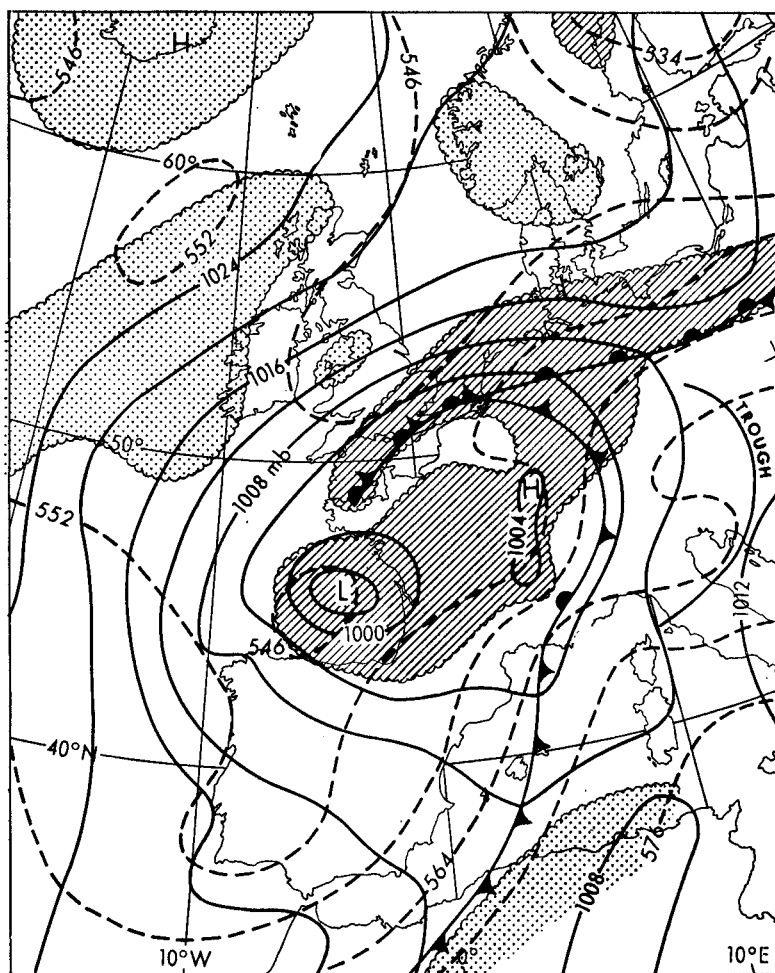


FIGURE 1—continued

(c) 12 GMT, 15 September 1968. Thickness values are in geopotential decametres. See also notes under Figure 1(a).

'rainfall day' (in the 24 hours from 09 GMT on the 14th to 09 GMT on 15th) were in a belt running north-eastwards from the east Hampshire border to just east of Maidstone in Kent. Several point falls greater than 100 mm were recorded near Tonbridge and Maidstone. A parallel belt of heavy falls from Croydon to Maldon in Essex had point falls over 90 mm but none in excess of 100 mm.

Rainfall totals in excess of 10 mm covered a wider area on 15 September;* most of the area south-east of a line from Weymouth to Spalding, including the whole of East Anglia, had more than 25 mm. Again the belts of heaviest rainfall ran in a south-west to north-east direction. The widest belt with totals greater than 50 mm, from Winchester to the Thames Estuary, including Clacton in Essex and Herne Bay in Kent, was approximately 50 km wide and had seven centres with recorded rainfall totals of more than 100 mm. These

*In this section dates refer to the 'rainfall day'.

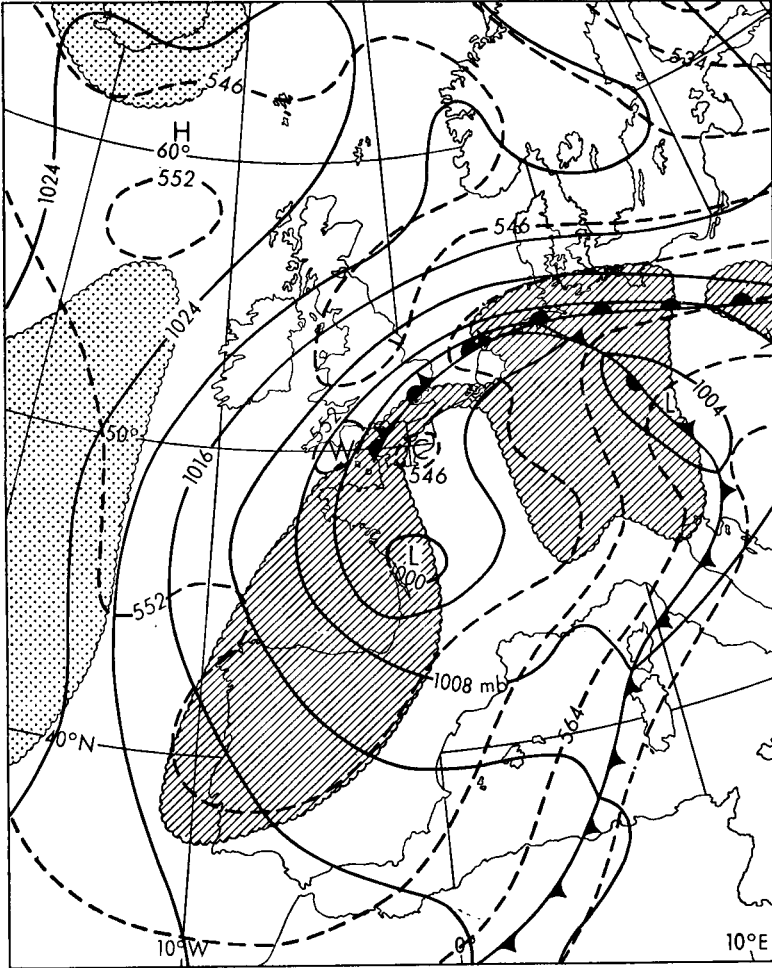


FIGURE 1—*continued*

(d) 00 GMT, 16 September 1968. Thickness values are in geopotential decametres. See also notes under Figure 1(a).

included the highest totals recorded for the rainfall day, 129.5 mm at Bromley in Kent and 123.7 mm and 124.5 mm at Godstone in Surrey. The second belt with totals greater than 50 mm was narrower, 15–25 km, over most of its length from Beaconsfield in Buckinghamshire widening to about 50 km as it crossed Norfolk and Suffolk to the coast with Great Yarmouth on the axis. Although a large part of this belt had recordings of more than 75 mm, there were only five reports of more than 100 mm.

The combined distribution for these two days from 09 GMT on 14 September to 09 GMT on 16 September (Figure 3) shows the area of heaviest falls from Hampshire, across north Sussex, Surrey and Kent and across the Thames to Essex. The highest two-day totals were reported in Essex—201.4 mm at Marsh Farm Sewage Works and 200.9 mm at Stifford Pumping Station—in the Tilbury–Purfleet area. (Other reports are given in Table I.) In these two days

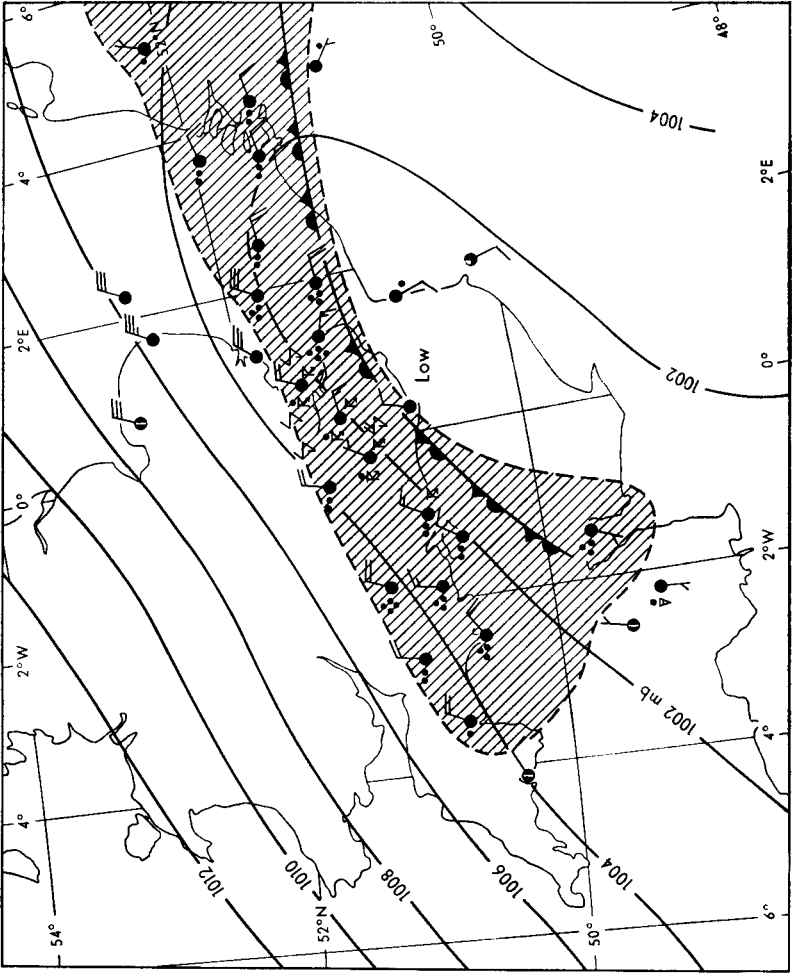


FIGURE 2—SIGNIFICANT WEATHER OVER SOUTHERN ENGLAND
ON 15 SEPTEMBER 1968
(a) 09 GMT thunderstorm location reports (SFLOCs) are included.
Shading shows the rain area.

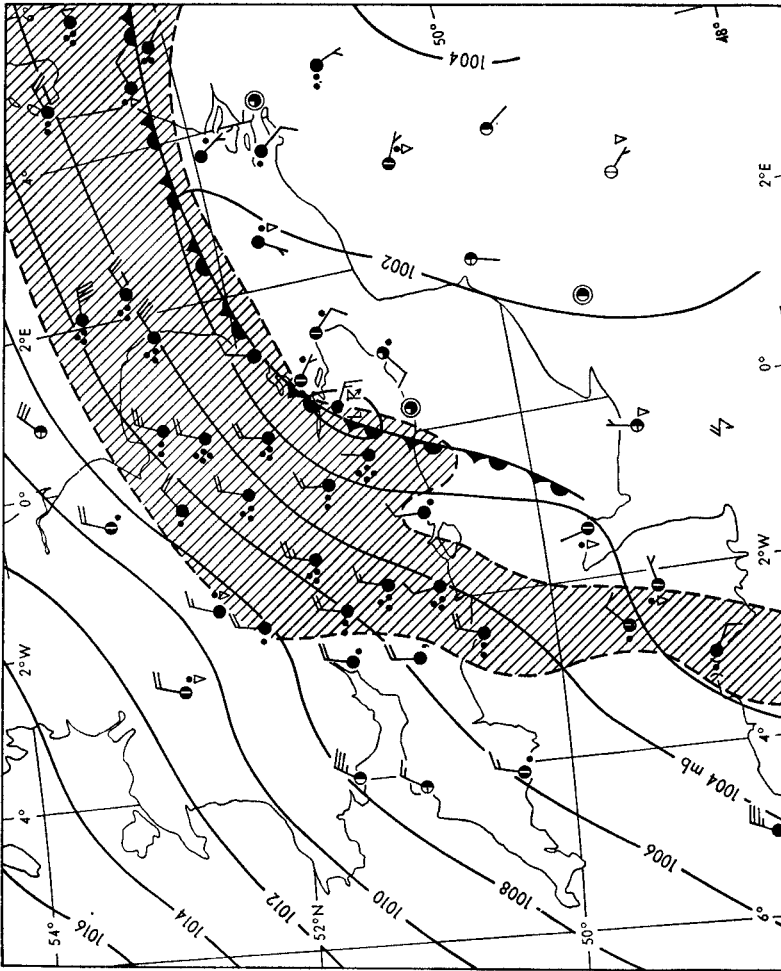


FIGURE 2—continued

(b) 18 GMT

Shading shows the rain area.

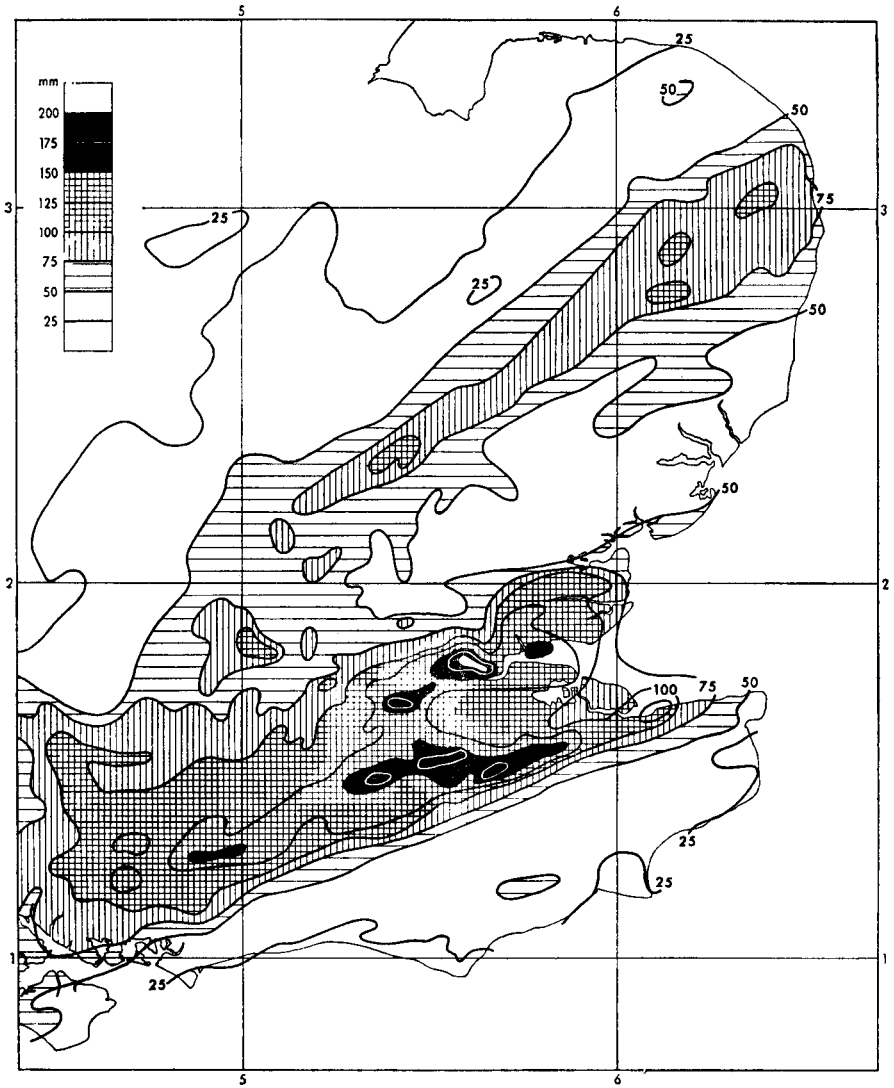


FIGURE 3—TOTAL RAINFALL FOR 14-15 SEPTEMBER 1968
National Grid Lines are shown at 100-km intervals.

most of south-east England and East Anglia had more than 5 per cent of its average annual rainfall. Part of Kent and Surrey, about 450 km², and an area of about 750 km² along the Thames Estuary had more than 20 per cent of their average annual rainfall. The highest percentages for the two days were in Essex at the two stations recording the highest rainfall totals with 39.0 and 39.7 per cent respectively. A further small amount of rain fell in the area on 16 September but totals were mainly less than 10 mm and were almost negligible compared with the amounts on the previous two days.

Autographic records show few intense short-period falls during the two days but do show that most of the two-day total of rain fell in 24 hours or less,

spanning the two rainfall days. The Broadfield, Crawley, chart shows the main rainfall beginning between 05 and 06 GMT on the 15th and continuing steadily until 13 GMT followed by slight rain for about 5 hours. At 18 GMT it began to rain steadily again and this lasted for 3 hours. This was a fairly typical pattern for stations in Kent and Surrey. North of the Thames the chart for Basildon shows two storms starting at 1630 GMT and 22 GMT on the 14th and this was followed by periods of slight rain until the end of the rainfall day. On the 15th it rained steadily for $5\frac{1}{2}$ hours from 10 GMT with further outbreaks of rain after 20 GMT. It was the storms of the 14th in this area which gave the more intense short-period falls. Across East Anglia most of the rain fell on the 15th starting between 14 and 15 GMT and continuing for 8 to 10 hours. This rain was generally less intense than that which occurred in Kent and Surrey earlier in the day.

Rainfall on previous days. Rainfall for the first 13 days of September was generally less than 50 mm and over quite a large part of the area it was less than 25 mm. Rain fell over the whole area during the first few days, but from the 5th to 9th inclusive most parts were dry. Rain was widespread over the area on the 10th but amounts were generally low. The 11th was dry over much of the area, but a few places in East Anglia recorded between 25 mm and 35 mm. The next two days were dry except for parts of Kent and Sussex. As a result of this, the soil moisture deficit, which on the 11th ranged from 10 mm to 100 mm, was quite large over most of the area.

Flooding and damage. Serious and widespread flooding occurred over Kent, Surrey and parts of Essex, Hertfordshire and Suffolk with localized flooding in many other parts of the area. In general, rivers reached their peak (maximum height) on the 16th and the water continued to spread on the 17th causing disruption to all forms of communication and many thousands of pounds' worth of damage.

The flow in the lower reaches of the River Mole was about four times that of January 1955 which was itself the highest recorded between 1930 and 1955. In Sussex at Park Mound the River Arun rose 5.2 m in 24 hours, from almost zero flow to the highest level ever recorded, and on the Rother the highest level previously recorded at Fittleworth was exceeded by 0.3 m. On both of these rivers and on many others the significant feature was the extra rainfall on the evening of the 15th. By the River Stour in Suffolk the flood was comparable with that of 1947. In the Kent River Authority area, flooding in the valleys of the Rivers Darent, Cray, Eden, Eden Brook and Bourne was far worse than any previously recorded. Besides these valley floods a great deal of flooding occurred remote from the rivers and before the rivers overflowed. The flow of a number of rivers and streams had to be estimated because the gauging stations were either flooded or bypassed by the flood waters.

The total area of land flooded, excluding the Sussex River Authority area for which information is not available, was estimated as 220 km² of which more than 100 km² were in the Kent River Authority area and 60 km² in the Thames Conservancy area. In this latter region it was the area flooded by just three tributaries of the Thames, the Mole, Wey and Loddon. The figure given for the Kent River Authority area includes 44 km² of marshland. Again excluding the Sussex River Authority area, almost 21 000 properties were flooded. Over 14 000 of these, of which 10 000 were residential, were in the area of the Thames

Conservancy, mainly in the valleys of the Mole and the Wey. It is reported that one factory alone suffered a loss of £500 000 including damage and loss of production.

A number of roads were impassable for varying lengths of time including the A 23 at Horley and Gatwick, the A 217 at Sidlow, the A 24 at Mickleham, the A 3 at the Kingston Bypass, Cobham and the Guildford Bypass, the A 281 at Shalford, the A 244 at Hersham, the A 329 near Reading, the A 23 at Brasted, the A 21 at Darent and the A 2 at the confluence of the Rivers Cray and Shuttle. At Tonbridge on the 15th all roads northwards were impassable owing to local flooding. Several bridges collapsed and others were damaged by the volume of water rushing under and round them. More details of damage are given in Table II.

Total cost of damage caused by the exceptionally heavy two-day rainfall of 14 and 15 September 1968 is impossible even to estimate. The loss of crops on agricultural land, and the damage to roads and bridges, and to public and personal property cannot even be listed completely.

TABLE I—HIGHEST RECORDED RAINFALL MEASUREMENTS

Station number		National grid reference	Total rain mm
14 September 1968			
294630	Hildenborough	TQ 51 571488	106.2
295005	Hadlow College	TQ 51 628497	113.0
295010	Hadlow Sewage Works	TQ 51 631491	114.3
297727	Brenchley Gardens, Maidstone	TQ 51 759561	107.7
297722	Mill Street, Maidstone	TQ 51 761555	110.5
290007	Cross Ness, Erith	TQ 51 485809	97.5
237466	Stifford Pumping Station	TQ 51 590802	85.1
236974	Marsh Farm Sewage Works, Tilbury	TQ 51 654756	83.3
235389	Basildon Sewage Works	TQ 51 737908	89.7
235519	Wickford	TQ 51 772921	99.1
15 September 1968			
288687	Bromley	TQ 51 399693	129.5
293572	Godstone Sewage Works	TQ 51 365505	123.7
292953	South Godstone Sewage Works	TQ 51 363478	124.5
291253	Priory Gardens, Orpington	TQ 51 465666	121.9
14/15 September (48-h totals)			
237466	Stifford Pumping Station	TQ 51 590802	200.9
236974	Marsh Farm Sewage Works, Tilbury	TQ 51 654756	201.4
236632	Canvey Island Pumping Station	TQ 51 800828	155.2
284974	Earlswood Sewage Works	TQ 51 275483	151.1
293572	Godstone Sewage Works	TQ 51 365505	168.4
297340	East Farleigh Lock	TQ 51 735535	162.3
297727	Brenchley Gardens, Maidstone	TQ 51 759561	157.7
297347	Barming Water Works, Maidstone	TQ 51 735548	153.4
293953	South Godstone Sewage Works	TQ 51 363478	189.8
288687	Bromley	TQ 51 399693	190.5
290200	Sundridge Pumping Station	TQ 51 489556	160.8
290060	Erith Sewage Works	TQ 51 523777	154.4
290070	Westwood Pumping Station, Surrey	TQ 51 425541	150.1
290241	Chevening Gardens, Sevenoaks	TQ 51 484577	162.6
290412	Stone Street, Kent	TQ 51 572549	176.2
294056	Paines Hill, Limsfield	TQ 51 412513	157.8
294630	Hildenborough	TQ 51 571488	171.0
295010	Hadlow Sewage Works	TQ 51 631491	165.1
295945	Yalding, Kent	TQ 51 690497	154.4
297707	Hockers Lane Pumping Station, Maidstone	TQ 51 788571	159.6
297455	College Road, Maidstone	TQ 51 757549	165.1

Note: Many of these values were reported in inches and have been converted to millimetres.

TABLE II—FLOOD DAMAGE

Thames Conservancy area*Area flooded*

River Mole between Molesey and Horley	21.2 km ²
River Wey between Weybridge and Farnham	21.5 km ²
River Loddon	18.3 km ²

Damage to bridges

River Mole	Betchworth Bridge	Loss of both parapets
	Brockham Bridge	Loss of one parapet
	Boxhill Bridge	Collapse of one arch
	Stoke D'Abernon (rail)	Displacement of girders
	Downside Bridge	Collapse of two arches
River Wey	Brockford Bridge	Collapse of one arch
	Brooklands	Partial collapse of span carrying services
Hoe Stream	Godalming (rail)	Collapse of one span
Cranleigh Waters	Shalford (A 281)	Collapse of arch

Flooding of properties (provisional figures)

Local authority*	Houses	Other premises
Aldershot M.B.	7	1
Chertsey U.D.	200	20-30
Crawley U.D.	150	included
Dorking and Horley R.D.	200	included
Easthampstead R.D.	8	0
Esher U.D.	8000	included
Farnborough U.D.	24	included
Farnham U.D.	220	included
Godalming M.B.	110	10
Guildford M.B.	300	160
Guildford R.D.	170	a few
Hambledon R.D.	400	included
Hartley Wintney R.D.	24	included
Leatherhead U.D.	315	50
Reigate M.B.	200	150
Walton and Weybridge U.D.	2000-2500	included
Wokingham U.D.	1000	not known
Wokingham M.B.	33	2
Wokingham R.D.	70	included

Kent River Authority area*Area flooded*

River Medway	26.9 km ²
River Bourne	2.6 km ²
River Eden & Eden Brook	15.6 km ²
River Darent	7.2 km ²
River Cray	2.8 km ²
River Shuttle	2.3 km ²
Warden Bay Drainage	0.3 km ²

Marshes

Allhallows, Grain	9.2 km ²
Higham Cliffe	24.8 km ²
East of Gravesend	3.8 km ²
Swanscombe	0.5 km ²
Dartford-Stone	2.3 km ²
Sea-salter	2.8 km ²
Hoo	0.3 km ²

* Local Authority areas are as before 1 April 1974. M.B., U.D. and R.D. denote Municipal Borough, Urban District and Rural District.

Properties flooded

	Houses	Others
Westerham	110	3
Brasted	18	0
Sundridge	12	2 including one bridge
Chipstead	61	3
Dunton Green	10	3
Riverhead	4	6
Sevenoaks	some houses	farm buildings
Kemsing	11	farm buildings
Otford	5	one bridge
Shoreham	34	4 + 2 bridges
Eynsford	20	2
Farmingham	6	2
South Darenth	53	0
Dartford	238	258
St Mary's Cray	12	0
Crayford	number not known	—
Edenbridge	140	36
Tonbridge { Hildenborough	362	—
Barden area	450	152
East Peckham	many houses and industrial properties	
Yalding	40	included
Maidstone	number not known	—
Hadlow	43	15

Essex River Authority area

Area flooded

Tilbury Marshes	2.0 km ²
East and West Tilbury Levels	2.0 km ²
Mardyke catchment	9.7 km ²

Properties flooded

	Houses	Others
Sudbury	1	0
Haverhill	168	—
Keddington	15	included
Sturmer	19	included
Clare and Stoke-by-Clare	13	included
Cavendish	34	included
Long Melford	15	included
Bures	21	included
Cornard	6	included
Stratford St Mary	18	included
Wickford	50	included
Southend	200	1
South Benfleet	30	1
Canvey Island	120	included
Purleigh	4	a few
Hawkwell-Hockley-Rochford	60	—
Fobbing	—	industrial premises
Rainham	40	—
Loxford Water area	20	—
Mayesbrook area	20	—

Lee Conservancy area

Area flooded

Rivers Lee, Mimram, Beane, Rib, Ash, Start	25.6 km ²
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Properties flooded

	Houses
River Beane upstream of Hertford	104
River Rib upstream of Hertford	140
Bishop Stortford	100
River Lee, Hertford to Hoddesdon	310

Greater London Council area

Area flooded	Houses	20.0 km ²
Properties flooded	3000	

Note: Many of the areas given in this table were supplied in acres or square miles and have been converted to square kilometres.

Part II of this paper will be published in October.

REFERENCES

1. BLEASDALE, A.; The rainfall of 14th and 15th September 1968 in comparison with previous exceptional rainfall in the United Kingdom. *J Inst Wat Engrs, London*, **24**, 1970, pp. 181-189.
2. BLEASDALE, A.; The year 1968, an outstanding one for multiple events with exceptionally heavy and widespread rainfall. *Brit Rainf 1968, London* (in press).

REVIEWS

The use of satellite pictures in weather analysis and forecasting, WMO *Technical Note* No. 124, by Ralph K. Anderson, Jerome P. Ashman, Golden R. Farr, Edward W. Ferguson, Galina N. Isayeva, Vincent J. Oliver, Frances C. Parmenter, Tatiana P. Popova, Rance W. Skidmore, Arthur H. Smith and Nikolai F. Veltischev (edited by R. K. Anderson and N. F. Veltischev). 280 mm × 215 mm, pp. ix + 275, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1973. Price: Sw. Fr. 60.

This publication is a revision of *Technical Note* No. 75, produced as a result of a recommendation of the Commission for Synoptic Meteorology at its fifth session (June-July 1970) that an updated version should be prepared and issued in loose-leaf form to facilitate subsequent updating. A welcome feature of this new version is the collaboration of U.S.S.R. experts and as a result the incorporation of pictures from the COSMOS and METEOR satellites and the addition of many references to work in the U.S.S.R.

As might be expected, the opportunity has been taken to present the whole subject in a more general and comprehensive way than was possible in 1966 when *Technical Note* No. 75 first appeared. Chapter I, 'General characteristics of visible and infra-red images', serves as an introduction and provides essential information on both visual and infra-red images and on the equipment used to produce them. Chapter II, 'Atlas of cloud types, cloud formations and underlying surfaces', presents the necessary information for the practice of picture interpretation. From then on, the emphasis is on the application of satellite data, to weather analysis in extratropical latitudes (Chapter III), to synoptic analysis in the tropics (Chapter IV) and to the estimation of useful meteorological parameters (Chapter V). One of the pleasing new features is the arrangement of pictures close to the appropriate text, making for easier reference.

Many forecasters still do not have direct access to satellite pictures but are dependent on nephanalyses. Nowhere in this publication is any guidance given for the preparation and use of nephanalyses nor indeed any information on the preparation and use of coded satellite information. It is well known that

satellite information has its maximum value when integrated with more conventional data. There is a tendency throughout, particularly in the sections on applications to analysis and forecasting in extratropical latitudes to neglect this aspect and to treat satellite data as existing in isolation. This is surely a mistake, leading inevitably to an over-academic approach. In particular, the section on the use of satellite pictures to forecast the evolution of synoptic-scale disturbances provides forecasting rules derived solely from picture interpretation. Forecasting in extratropical areas is now more dependent on the use of numerical models and it is more relevant to know how satellite information can be incorporated in analyses to best advantage. Some information on this is given in the last chapter. This is obviously a most important subject particularly at the present time when the effect of data shortages on the performance of numerical models is only too evident.

Meteorologists everywhere will welcome this revised version and will look forward to subsequent extensions incorporating wider concepts of the use of satellite pictures in analysis and forecasting.

T. H. KIRK

Partial differential equations of mathematical physics, by Tyn Myint-U. 250 mm × 170 mm, pp. xiv + 365, *illus.*, Elsevier/Excerpta Medica/North-Holland Associated Scientific Publishers, Jan van Galenstraat 335, Amsterdam, The Netherlands, 1973. Price: 43.50 Dfl.

The title is the same as or similar to that of a number of other mathematical textbooks that are available and its contents follow fairly closely the traditional treatment of the subject. After the introduction and derivation of the equations for the physical problems, the canonical forms and general properties of second-order partial differential equations are treated and this leads on to the initial value or Cauchy problem. After a digression to derive the main results in the theory of Fourier series, the method of solution by separation of variables is described and illustrated. The Sturm–Liouville equations and some special functions are included in the chapter on eigenvalue problems. Solution of boundary-value problems in two dimensions with Dirichlet, Neumann and mixed boundary conditions follows. The last three chapters deal with the use of Green's functions to obtain solutions, with integral transforms and with equations in three or more space dimensions.

The contents are selective, and the book cannot rival more comprehensive treatises such as Courant Hilbert. But the selection is well made so that the argument proceeds without too much need for digression. The approach is based on the mathematical problems and their solution, the physical systems in which the equations occur entering only briefly in the initial derivation. The book is therefore not appropriate for readers who are looking for physical insight into the equations or for methods for solving practical problems by numerical methods.

With a text covering such a well-known field the main question that arises is probably 'For what kind of reader can it be recommended?'. Writing as a meteorologist whose mathematics has grown rusty, the reviewer found it suitable for the purpose of reminding him of the mathematical basis of many

problems arising in meteorology. Almost all the important equations from this source are treated, and, from this same point of view, very little of the total content could be considered redundant. I suspect most dynamical meteorologists could read it with considerable profit. For clarity of style and printing the text is admirable. Those with the necessary mathematical background will find it a pleasure to read. There is a wealth of problems of varying difficulty which makes it especially suitable also for students fairly new to the subject.

While, therefore, it can hardly be recommended as essential reading, this book should find a grateful readership among those who are looking for a clear, straightforward and comparatively easy account of the mathematical theory of the standard partial differential equations which occur in physical problems.

A. GILCHRIST

The physics of air-sea interaction, by S. A. Kitaigorodskii. 250 mm × 175 mm, pp. vi + 237, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), John Wiley & Sons Ltd., Baffins Lane, Chichester, Sussex, 1974. Price: £7.65.

Active research in the field of air-sea interaction now involves a range of topics too broad to be discussed comprehensively in a single textbook. The present monograph is concerned solely with small-scale interactions between ocean and atmosphere and its scope is correspondingly limited, but this restriction in subject matter has given the author enough space to develop some of his ideas in considerable detail. Kitaigorodskii has carried out research in a number of aspects of small-scale processes near the sea surface and he admits that the contents of his book reflect his particular interests; thus, while he has written in most cases with considerable authority, there is inevitably selectivity also, and some imbalance.

The text is divided into three main sections. The first occupies roughly half the book and is concerned with the dynamics of the near-surface atmosphere including vertical turbulence transfers. This part of the book is likely to be of most interest to meteorologists. It begins with an introductory chapter on flow over a solid boundary and follows with descriptions of the changes which result in the flow when the rigid boundary is replaced by the waving sea surfaces. The section concludes with empirical data on the exchange coefficients for vertical transfers of momentum, heat and water vapour, and the effects of departures from neutral density stratification. Of particular interest is the discussion of the complex (and as yet undiscovered) relation between drag coefficient, wind speed and sea state.

The second main section is concerned with ocean waves. Dimensional arguments are used to derive the principal features of spectra of fully developed waves, and of waves after limited fetch or limited duration of wind. A brief description is given of the Miles-Phillips theory of wave development.

The final section deals with vertical mixing processes in the upper ocean. This is probably the least satisfactory part of the book, and Kitaigorodskii himself writes 'The . . . section appears to be premature'. There is a considerable amount of empiricism and while several problems are formulated, few

satisfactory answers emerge, even, for example, when important factors such as existing stratification or time dependence are omitted from discussions of wind mixing.

The translation suffers from a few flaws which careful editing by a micro-meteorologist or oceanographer would have eliminated. For example, it is unusual to talk of a 'deep minimum' in the power spectrum of wind velocity (p. 24). The retention of conventional Russian notation hinders easy reading: examples are P for air density and q_0 , W_E for the vertical fluxes of heat and water vapour. However, in spite of the volume's restricted scope and its blemishes it is a welcome addition to the literature of air-sea interaction. The price is no higher than one expects in these inflationary times.

N. THOMPSON

OFFICIAL PUBLICATION

The following publication has recently been issued: *Annual report on the Meteorological Office* 1973, London, HMSO, 1974. Price: £1.10.

The Director-General, in the foreword to his report for the year ending 31 December 1973, highlights the marked increase in demand for meteorological information from industry and the general public. The number of direct inquiries to the Office reached an all-time record of 1.75 million, while another all-time record of 15.5 million calls were made to the Post Office Automatic Telephone Weather Service.

The computer-based forecasts were further refined during the year, but the Director-General stresses the difficulties of maintaining an adequate network of observations, particularly over the oceans, and warns that any deterioration of the network could have an adverse effect on the accuracy of weather forecasts.

Activity in research was maintained at a high level. Work on the development of mathematical models to simulate and perhaps predict the behaviour of the atmosphere on relatively long time-scales continued. Anomalies in sea surface temperatures can have far-reaching effects on the development of weather patterns and one very interesting experiment strongly suggested that an area of abnormally warm ocean off West Africa was an important factor in producing the very cold winter of 1962-63.

The production of nitrogen oxides in the stratosphere by supersonic transport aircraft and their possible effects on ozone concentration at high levels have aroused considerable controversy. Calculations by Meteorological Office scientists indicate that the quantities of nitrogen oxides injected into the stratosphere by nuclear test explosions in the 1950s and 1960s were equivalent to those likely to be produced by 1000 Concorde each flying 7 hours a day. Moreover, analysis of world-wide ozone reports before and after the nuclear explosions fails to reveal any detectable changes in ozone content.

HONOUR

The following appointment to the Imperial Service Order was announced in the Queen's Birthday Honours List, 1974:
Mr H. C. Shellard, Principal Scientific Officer, Met O 3.

OBITUARY

It is with regret that we have to record the death of Mr P. Jenkins, Assistant Scientific Officer, Met O 2, on 31 May, 1974.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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RETIREMENT OF MR R. F. JONES AND DR F. PASQUILL

On 7 September 1974 the Meteorological Office lost the services of two of its senior scientists. Both Mr R. F. Jones and Dr F. Pasquill retired on that day after many years' service in the Office.

Mr R. F. Jones

Mr R. F. Jones joined the Meteorological Office as a Technical Officer in 1938, having graduated from the University of Oxford in both Mathematics and Physics. In common with most recruits at that time of pre-war expansion, he soon found himself engaged on forecasting duties first at the airfields of South Cerney and Aldergrove and later, during the war, at Headquarters Coastal Command and as officer-in-charge of the Meteorological Office at Nassau in the Bahamas.

The end of the Second World War found Mr R. F. Jones at the Central Forecasting Office at Dunstable, but his career in meteorological research began shortly afterwards and he was to continue in research posts until his retirement. In 1946 the Meteorological Office acquired a Royal Air Force radar station for the purpose of exploiting radar to study clouds and precipitation. Mr R. F. Jones was placed in charge of the investigations, and over the following seven years he made important contributions to radar meteorology using the obsolescent war-time radars at East Hill, a few miles from Dunstable. The importance of this work was recognized by the award to him of the L. G. Groves Memorial Prize for Meteorology in 1953.

In 1953 Mr Jones moved to the Meteorological Office Headquarters in Kingsway, London, to join the branch concerned with research in atmospheric physics. At that time there was relatively little laboratory work in atmospheric physics conducted in the Office, but Mr Jones made important contributions to the application of meteorological knowledge to practical aviation problems. He took an active part in the inquiries into the problems of flame-out on the Britannia aircraft, and into the disaster at Munich when an aircraft crashed during take-off in snow and slush. Mr Jones served on several working groups of the World Meteorological Organization and contributed two important *Technical Notes*—on meteorological radar and ice formation on aircraft which were published by the Organization.

Mr Jones was promoted to Senior Principal Scientific Officer in 1960 to head the Atmospheric Physics Branch and subsequently spent four years as Assistant Director in charge of Special Investigations. In 1971 he was promoted to Deputy Chief Scientific Officer and took charge of all Physical Research within the Research Directorate. One of his main responsibilities during this period was the organizing of the United Kingdom contribution to the GARP Atlantic Tropical Experiment—a major international expedition in which four British ships took part as well as the Hercules aircraft of the Meteorological Research Flight. During this period he also undertook the quite onerous duties of the Treasurer of the Royal Meteorological Society.

With Mr Jones's retirement the Meteorological Office will miss his broad experience and wise technical judgement.

Dr F. Pasquill

Dr Pasquill joined the Meteorological Office in 1937 having graduated at Durham with First Class Honours and done some post-graduate work. He soon found himself a member of the small meteorological research team which was maintained at Porton for studies of atmospheric diffusion in support of the work of the Chemical Defence Research Establishment. Frank Pasquill remained a member of this research group until 1946 during which period he spent some time in Australia studying diffusion under semi-tropical conditions.

In the post-war reorganization of the Meteorological Office it was decided that the application of meteorology to agriculture should be developed and a small research group was established at Cambridge with Dr Pasquill in charge. At Cambridge he made important advances in the application of turbulence theory to the measurement of evaporation from crops and in 1950 he was granted the degree of Doctor of Science by Durham University in recognition of his researches and also received the L. G. Groves Memorial Prize for Meteorology.

For four years in the early 1950s Frank Pasquill was at the Atomic Energy Research Establishment advising on the diffusion of material in the atmosphere at a time when the dangers of the release of radioactivity into the atmosphere were being faced seriously for the first time. However, 1954 saw him back at Porton and in charge of the meteorological research there after being granted Special Merit promotion to Senior Principal Scientific Officer in recognition of his major contributions to the theory of atmospheric diffusion and its applications. In 1961 Dr Pasquill moved to the Meteorological Office at Bracknell, taking responsibility for all research in the Office on the atmospheric boundary layer and under his guidance the facilities for such studies were developed at Cardington to provide a unique capability of investigating the whole of the planetary boundary layer from a tethered balloon cable. Further Special Merit promotion to Deputy Chief Scientific Officer followed in 1966 in recognition of his continued outstanding contributions to the understanding of atmospheric turbulence.

Dr Pasquill has played an important role in many scientific activities outside the Meteorological Office and is known internationally as one of the world's leading authorities on atmospheric turbulence. In 1962 he published a book on atmospheric diffusion which is a standard work on the subject. He was editor of the *Quarterly Journal* from 1961 to 1964 and President of the Royal Meteorological Society from 1970 to 1972. He has also contributed considerably to the

solution of many practical problems arising in regard to atmospheric pollution, being consulted by many individuals and organizations both national and international on the diffusion of pollutants.

The Meteorological Office will seriously miss the services of Mr R. F. Jones and Dr F. Pasquill who have both played an important part in moulding its research activities over many years. Their many friends and colleagues in the Meteorological Office and in the wider scientific community at home and abroad will, I am sure, wish them both a long and happy future.

J. S. SAWYER

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AN ASSESSMENT OF TOPOGRAPHICAL CONTROLS ON THE DISTRIBUTION OF RAINFALL IN THE CENTRAL PENNINES

By GOH KIM CHUAN and J. G. LOCKWOOD
University of Leeds

Summary. This study attempts to assess the role of relief on both annual and seasonal rainfall distributions in the central Pennines. Instead of using the common relief parameters such as spot altitude, exposure, aspect, etc., mean relief is introduced. Very high correlations are obtained for the east Pennine region when mean altitude at 8-km radius is applied. The relationship in west Pennines is not so good though statistically significant. It is suggested that mean altitude at 8-km radius is the best parameter for such analysis, especially in east Pennines. The study also indicates that the wind structure is more complex over the west Pennine region than over the east.

Introduction. The effects of topography on annual and seasonal rainfall distribution have long been recognized.¹ The lifting effect *per se* and/or the triggering effect of mountain slopes on rain-bearing winds cause substantially higher amounts of precipitation on higher slopes than in the lowlands. This does not necessarily mean that precipitation will progressively and indefinitely increase upslope on a mountain range. This appears to be so in the British Isles, but work in the humid tropics has shown that the greatest precipitation occurs on the mountain slopes and does not coincide with the highest altitudes (Braak;² de Boer;³ Dale⁴).

Several objective attempts had been conducted to assess statistically the influence of altitude and other topographic parameters on the distribution of annual precipitation. One of the earliest studies was conducted in western Colorado by Spreen⁵ who applied graphical correlation techniques to determine the controlling influence of spot altitude, rise, orientation and exposure on mean seasonal precipitation. This was followed by Burns⁶ in California. He correlated annual precipitation with topographic variables of altitude, slope, rise, aspect, and zone of influence using the same technique as Spreen. These studies suggest that altitude is an important parameter in rainfall distribution. However, not all studies in the United States have provided similar results.

Schermmerhorn⁷ discovered that for western Oregon and Washington, station altitude alone does not explain much of the variation in the distribution of annual precipitation.

In the United Kingdom, assessments of the annual precipitation variation with altitude have been carried out by Rodda,⁸ Unwin⁹ and Bleasdale and Chan.¹⁰ Except for Unwin who used trend surface analyses, these made use of either simple linear regression or multiple correlation techniques. In these studies station spot altitude was the main topographic variable used and it was found to be the main determining factor in the distribution of annual precipitation. Other factors such as slope and exposure were the secondary variables used.

This study concerns a zone of northern England from Liverpool to north of Morecambe and extending from the coast of Lancashire on the west to the coast of Yorkshire in the east thus encompassing both sides of the Pennines (Figure 1). Similar techniques to those used by earlier workers were applied.

Relationships between annual precipitation and altitude were determined for two regions—west and east Pennines with the mountains as the divide. As the predominant rain-bearing winds come from the west or south-west this relationship may vary between one zone which is basically windward and the other which is in the 'rain-shadow'.

In earlier studies station spot altitudes were correlated against annual precipitation. Although this parameter was observed to be statistically significant, the regression coefficients obtained were not convincingly high, for in most cases it accounted for only some 50–60 per cent of the variance. It was because of this relatively low value that secondary topographic parameters were used so as to increase the correlation values and hence the percentage of explained variance, but there must be some doubt about the validity of using secondary factors, which themselves are highly correlated, as so-called independent variables. This is especially true of the regions under consideration. This study attempts to dispense with the secondary variables by using mean altitude as the sole factor.

Most of the studies in the United Kingdom cited made use of long-term precipitation values, i.e. annual totals. As a considerable amount of summer precipitation can be attributed to localized convectional thunderstorms, the use of annual precipitation alone introduces some bias into the analysis. Shaw¹¹ shows that at some rainfall stations—which are located in the region under study—e.g. Rotherham and Nelson, more than 90 per cent of summer rainfall comes under the category of 'thunderstorm'. Also Duckstein *et alii*¹² in their study of rainfall in the Santa Catalina Mountains near Tucson, Arizona stated 'when annual precipitation is separated into that resulting from winter frontal systems and summertime air mass convective storms, it is noted that winter precipitation is increased more than four-fold at the 2100 metres (7000 feet) as compared to that found at 1200 metres (4000 feet). For these same elevations, summer rainfall is not quite doubled'. Thus an attempt was made to look at the precipitation–elevation relationships over short-term time periods of season, month and day.

Although all the above intended analyses would be helpful in the understanding of the role of elevation on precipitation, they are not ends in themselves. They are intended to provide a start for the analysis of individual storms which are the soundest basis for determining topographic effects on

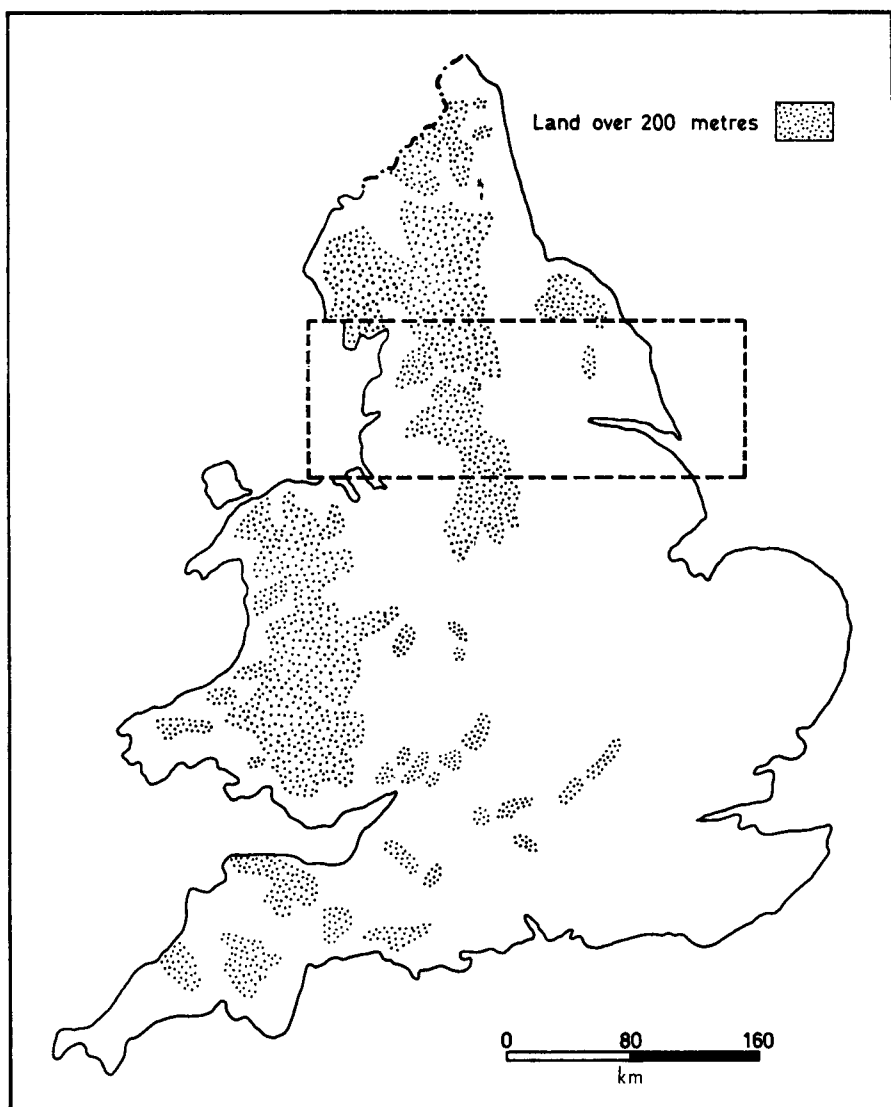


FIGURE 1—AREA OF STUDY, CENTRAL PENNINES
The area is denoted by a pecked rectangle.

precipitation. It is hoped that from such studies some models of storm precipitation on both sides of the Pennines can be produced. However, this last aim is not within the scope and content of this paper.

Analysis. Altogether about 200 rainfall stations were used in this analysis—138 stations in the east Pennines and 65 in the west Pennines. Their distribution according to altitude is given in Table I. As a first step simple linear regression was carried out between station spot altitudes and their mean annual precipitation (1916–50) as obtained from the *British Rainfall Supplement* 1961–1965¹³ for

TABLE I—NUMBER OF RAINFALL STATIONS ACCORDING TO MEAN ALTITUDE AT 8-KM RADIUS IN EAST AND WEST PENNINES

Mean altitude (8-km radius) metres	West Pennines	East Pennines
0-100	31	71
100-200	12	26
200-300	13	23
300-400	6	14
400-600	3	4
Total stations	65	138

both the east and west Pennine regions. Next, similar analyses were carried out between mean annual precipitation and station mean altitudes starting from 1 kilometre radius and extending outwards in the four cardinal directions of the compass. Topographical maps of the area to the scale 1:63 360 were used to obtain these values. The purpose of doing this was to determine the highest correlations between secondary variables of exposure and maximum rise with mean annual precipitation. As such an exercise would be too tedious to be carried out for 200 stations, a test was made for a smaller area involving 35 stations, the results of which are shown in Table II. While other parameters were also tested—slope, rise and aspect—exposure and maximum relief range were considered to be the most meaningful. Distance from the divide of the Pennines was also used as another secondary factor in preference to distance from the west coast. Multiple correlations were then carried out between mean annual precipitation and:

- (a) spot altitude as the main variable and distance from the divide, exposure and maximum rise as secondary variables and
- (b) mean altitude as the main variable and the others as secondary variables.

Analysis of mean monthly values (1961-66), mean seasonal precipitation (1961-66) and mean daily precipitation (1963-72) for east Pennines alone were later carried out.

Results

Mean annual precipitation. Table III shows regression coefficients between mean annual precipitation and station spot altitudes as well as mean altitudes over varying radii for west and east Pennine regions. It is evident that the use of mean altitudes gives substantially higher correlation values than spot altitudes in both the regions. However, an important feature indicated by the results is the significantly higher values obtained in the east Pennine region than in the west. Another feature that emerges for the east Pennine region is that the correlation coefficients progressively increase with increasing radius from rainfall stations until the highest value of 0.95 is attained at 8-km radius after which the coefficients start to decline. In the west Pennine region such a trend is not so obvious. Up to the 20-km radius, it is difficult to identify the radius at which the coefficient is the highest. The range between the highest and lowest correlation coefficients is 0.05 which is negligible indeed.

Tables IV and V show the results of multiple linear correlation analysis for both the east and the west Pennines using spot altitude and mean altitude (8-km radius) respectively. It is evident that for the east Pennines the inclusion of

TABLE II—CORRELATION COEFFICIENTS BETWEEN MEAN ANNUAL RAINFALL (1916–50) AND EXPOSURE AND MAXIMUM RISE IN EAST PENNINES (35 STATIONS)

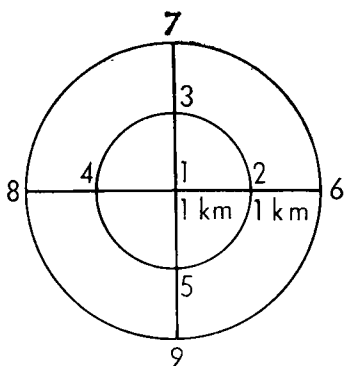
Radius km	Exposure	Maximum rise
1	–0·333	0·476
2	–0·348	0·466
3	–0·416	0·497
4	–0·350	0·580
5	–0·381	0·692
6	–0·370	0·643
7	–0·341	0·544

Exposure—the angle expressed in radians in which there is no topographical feature of height in excess of or equal to that of the gauge.

Maximum rise—the range of height between the highest and lowest points within radius specified.

TABLE III—CORRELATION COEFFICIENTS BETWEEN MEAN ANNUAL RAINFALL (1916–50) AND MEAN AND SPOT ALTITUDES FOR WEST AND EAST PENNINES

Radius km	West Pennines Correlation coefficient	East Pennines Correlation coefficient
1	0·6775	0·8807
2	0·7184	0·8884
3	0·7379	0·8952
4	0·7437	0·8980
5	0·7421	0·9012
6	0·7362	0·9204
7	0·7334	0·9384
8	0·7305	0·9539
9	0·7272	0·9420
10	0·7281	0·9023
11	0·7354	0·8642
12	0·7418	0·8557
13	0·7402	
14	0·7368	
15	0·7350	
16	0·7340	
17	0·7335	
18	0·7305	
19	0·7321	
20	0·7318	
Spot altitude	0·5957	0·8437



Mean altitude—obtained by averaging the spot altitudes of four cardinal points of compass and that of the station itself at varying radii. At 1-km radius, the sum of spot altitudes at points 1 to 5 is divided by 5 and at 2-km radius the sum of spot altitudes at points 1 to 9 is divided by 9. This is done for all the radii specified.

Spot altitude—the height in metres above sea level of the rain-gauge.

TABLE IV—MULTIPLE CORRELATION COEFFICIENT VARIANTS AND MATRIX OF SIMPLE CORRELATION COEFFICIENTS BETWEEN MEAN ANNUAL RAINFALL (1916–50) AND (a) SPOT ALTITUDE AND SECONDARY VARIABLES AND (b) MEAN ALTITUDE (8-km RADIUS) AND SECONDARY VARIABLES FOR EAST PENNINES (138 STATIONS)

(a)	Mean annual rainfall	Spot altitude	Distance from Pennines	Exposure	Maximum rise
Mean annual rainfall	1.0000	0.8437	−0.6365	−0.4462	0.8549
Spot altitude		1.0000	−0.6828	−0.3831	0.8371
Distance from Pennines			1.0000	0.5211	−0.6617
Exposure				1.0000	−0.5330
Maximum rise					1.0000
$r = 0.8843$					
$r^2 = 0.78$					
(b)	Mean annual rainfall	Mean altitude	Distance from Pennines	Exposure	Maximum rise
Mean annual rainfall	1.0000	0.9539	−0.6365	−0.4462	0.8549
Mean altitude		1.0000	−0.7125	−0.5299	0.9284
Distance from Pennines			1.0000	0.5211	−0.6617
Exposure				1.0000	−0.5330
Maximum rise					1.0000
$r = 0.9605$					
$r^2 = 0.92$					

TABLE V—MULTIPLE CORRELATION COEFFICIENT VARIANTS AND MATRIX OF SIMPLE CORRELATION COEFFICIENTS BETWEEN MEAN ANNUAL RAINFALL (1916–50) AND (a) SPOT ALTITUDE AND SECONDARY VARIABLES AND (b) MEAN ALTITUDE (8-km RADIUS) AND SECONDARY VARIABLES FOR WEST PENNINES (65 STATIONS)

(a)	Mean annual rainfall	Spot altitude	Distance from Pennines	Exposure	Maximum rise
Mean annual rainfall	1.0000	0.5957	−0.3458	−0.4774	0.3665
Spot altitude		1.0000	−0.6321	−0.2316	0.2191
Distance from Pennines			1.0000	0.5214	−0.2603
Exposure				1.0000	−0.2976
Maximum rise					1.0000
$r = 0.7514$					
$r^2 = 0.56$					
(b)	Mean annual rainfall	Mean altitude	Distance from Pennines	Exposure	Maximum rise
Mean annual rainfall	1.0000	0.7260	−0.3458	−0.4774	0.3665
Mean altitude		1.0000	−0.7167	−0.4796	0.3306
Distance from Pennines			1.0000	0.5214	−0.2603
Exposure				1.0000	−0.2976
Maximum rise					1.0000
$r = 0.8086$					
$r^2 = 0.65$					

Note: r denotes multiple correlation coefficient.

secondary factors to spot altitude does not produce substantially higher coefficients than those obtained by simple regression with the mean altitude alone. The results indicate that the use of mean altitude—in this case 8-km radius—takes into account the combined effects of spot altitude and all secondary variables that may exert influence on the rainfall distribution.

In the west Pennines very similar results were also obtained although the correlation coefficients are generally lower than those obtained in the east Pennine region. The inclusion of secondary variables with spot altitude gives a multiple correlation coefficient of 0.75 which is comparable to 0.73 obtained from the use of mean altitude alone. However, the use of mean altitude together with the secondary variables gives slightly better results of 0.80.

Using the mean altitude at 8-km radius for east Pennines the following regression equation was obtained:

$$y = 2.023x + 564.27 \quad \dots (1)$$

where

y = the predicted annual precipitation in millimetres,

x = the mean altitude at 8-km radius in metres.

It is interesting to note that at a sea-level station the predicted rainfall value, 564.27 mm, is very close to the actual mean observed values at stations such as Manby (spot altitude 15 m, mean annual rainfall 579.1 mm) and Thorne (spot altitude 5 m and mean annual rainfall 578.0 mm). The use of spot altitude produces an overestimation of precipitation at lowland stations.

For the west Pennine region the corresponding regression equation is:

$$y = 1.890x + 916.29. \quad \dots (2)$$

In contrast to the east Pennine equation this equation gives larger values for sea-level stations than those actually experienced at stations near the coast. Figure 2 shows the extent of scatter of stations along the regression lines for both regions. The excess of predicted rainfall over observed rainfall at sea-level stations on the west coast is evident from Figure 2 (top diagram). Figures 3 and 4 show the predicted rainfall map for both east and west Pennine regions based on equations (1) and (2) respectively. A comparison of Figures 3 and 4 with Figure 5 shows the close relationship between the isohyets and the mean relief pattern, especially in the east Pennines. The distribution of the anomalies or residuals in the east Pennines is shown in Figure 6. A separate analysis was also carried out for west Yorkshire involving 100 stations and the rainfall map (Figure 7) was plotted from the following equation:

$$y = 2.356x + 534.40 \quad \dots (3)$$

where y and x have the same meanings as in equation (1) above.

Seasonal precipitation. This aspect of the analysis was confined to the east Pennine region. Table VI shows the correlation coefficients between mean elevation (8-km radius) and mean monthly rainfall (1961-66). Consistently high correlations are obtained for all months especially during the winter months of November-April. The results indicate that even in the summer months the significant rainfalls experienced in this region are well distributed over large areas, i.e. about 100 km in diameter.

Table VII shows the mean seasonal correlation coefficients based on the 2-4-2-4 seasonal divisions, and the mean 24-hour seasonal rainfall (1963-72). As before, consistently high correlations between rainfall and mean elevation are obtained.

Conclusions. Spot altitude is normally used in this type of analysis. In most cases—depending on the location of the areas studied and their configura-

TABLE VI—CORRELATION COEFFICIENTS BETWEEN MEAN MONTHLY RAINFALL (1961-66) AND MEAN ALTITUDE AT 8-KM RADIUS FOR EAST PENNINES

Month	Correlation coefficient
Jan.	0.9534
Feb.	0.9607
Mar.	0.9264
Apr.	0.9590
May	0.8951
June	0.8137
July	0.8441
Aug.	0.8358
Sept.	0.8372
Oct.	0.9034
Nov.	0.9424
Dec.	0.9133

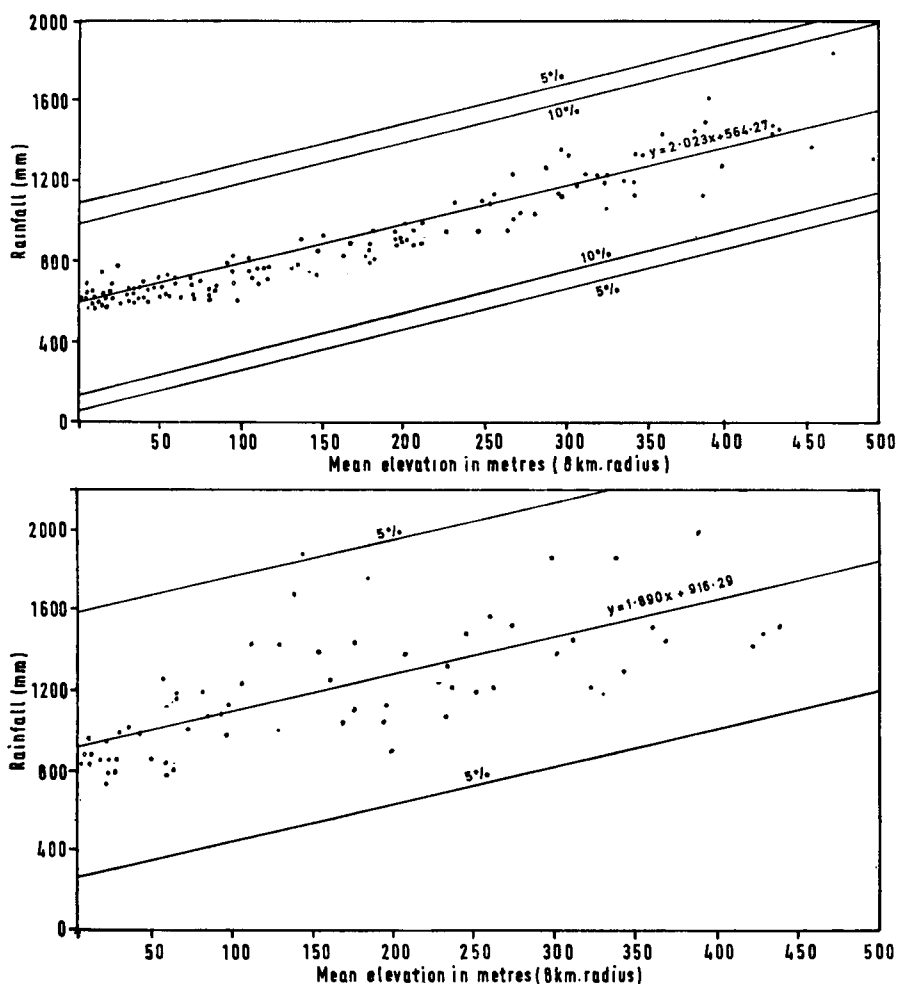


FIGURE 2—MEAN ANNUAL RAINFALL (1916-50) AND REGRESSION LINES East Pennines in top diagram, west Pennines in bottom diagram.

TABLE VII—CORRELATION COEFFICIENTS BETWEEN (a) MEAN SEASONAL RAINFALL (1961–66) AND (b) MEAN 24-HOUR SEASONAL RAINFALL (1963–72) AND MEAN ALTITUDE AT 8-KM RADIUS IN EAST PENNINES

Season	Correlation coefficient (a)	Correlation coefficient (b)
Nov.–Feb.	0.9493	0.9121
Mar.–Apr.	0.9303	0.8937
May–Aug.	0.8707	0.8183
Sept.–Oct.	0.8811	0.7599

Note: Mean 24-h seasonal rainfall is mean monthly rainfall divided by the number of rain days.

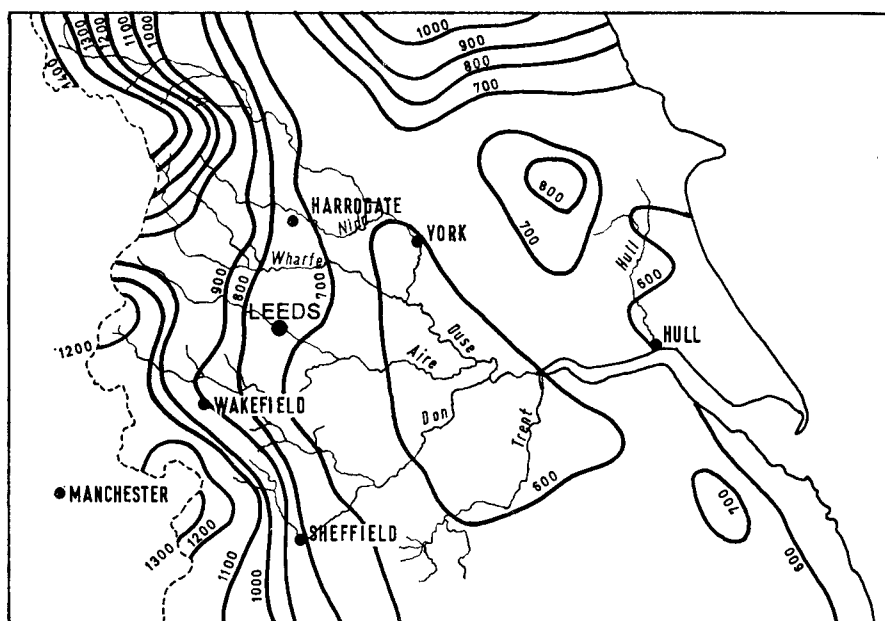


FIGURE 3—MEAN ANNUAL RAINFALL (1916–50) OF EAST PENNINES DERIVED FROM EQUATION (1)
Rainfall values are in millimetres.

tion—it accounts for some 50–60 per cent of the variation in the distribution of annual precipitation. The use of secondary variables in such studies helped to improve the correlation coefficients. This study has shown that the mean altitude over an 8-km radius around rainfall stations is more useful and the resultant equation obtained is simple and gives a very close estimate of actual mean annual values. This is especially true for the east Pennines. It is difficult to separate the influence of secondary variables on rainfall distribution and the problem which is frequently overlooked is the high correlation existing between topographic variables which have been regarded as independent variables.

The poor correlation between relief and rainfall distribution in the west Pennine region is difficult to explain. From Figure 2 it is noticeable that high rainfall amounts are recorded at 100–150 m after which there is a decrease and then a subsequent increase. The high proportion of variance not accounted for by topography may be caused by the prevailing south-westerly airstream

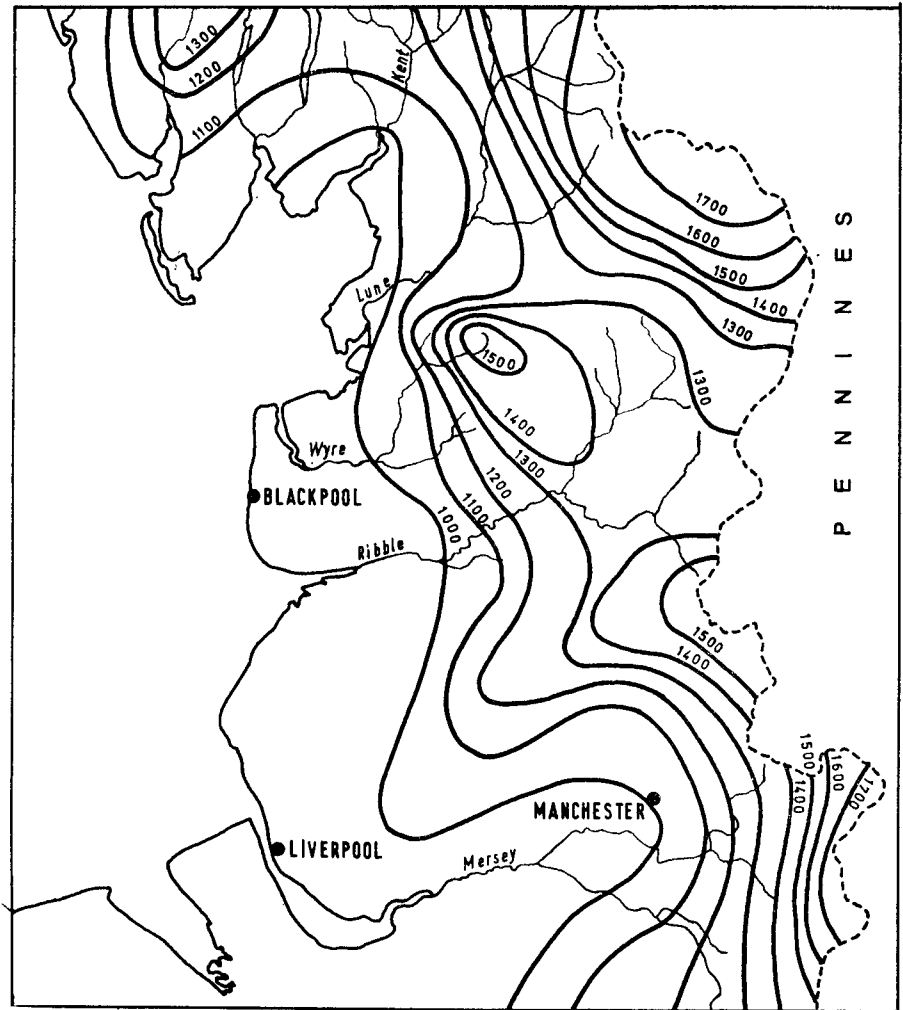


FIGURE 4—MEAN ANNUAL RAINFALL (1916-50) OF WEST PENNINES DERIVED FROM EQUATION (2)

Rainfall values are in millimetres.

starting to ascend some distance upstream of the Pennines and by the complexity of the airflow over the windward slopes.

Seasonal and monthly precipitation analyses in the east Pennines provide as high correlations as the annual precipitation analysis. This indicates that the rainfall in this region is rather widespread and that the relationship between rainfall and relief in summer months is not much affected by convective thunderstorms.

The good results from the east Pennines indicate that a study of rainfall-relief relationships in individual storms may be worth while in this particular region.

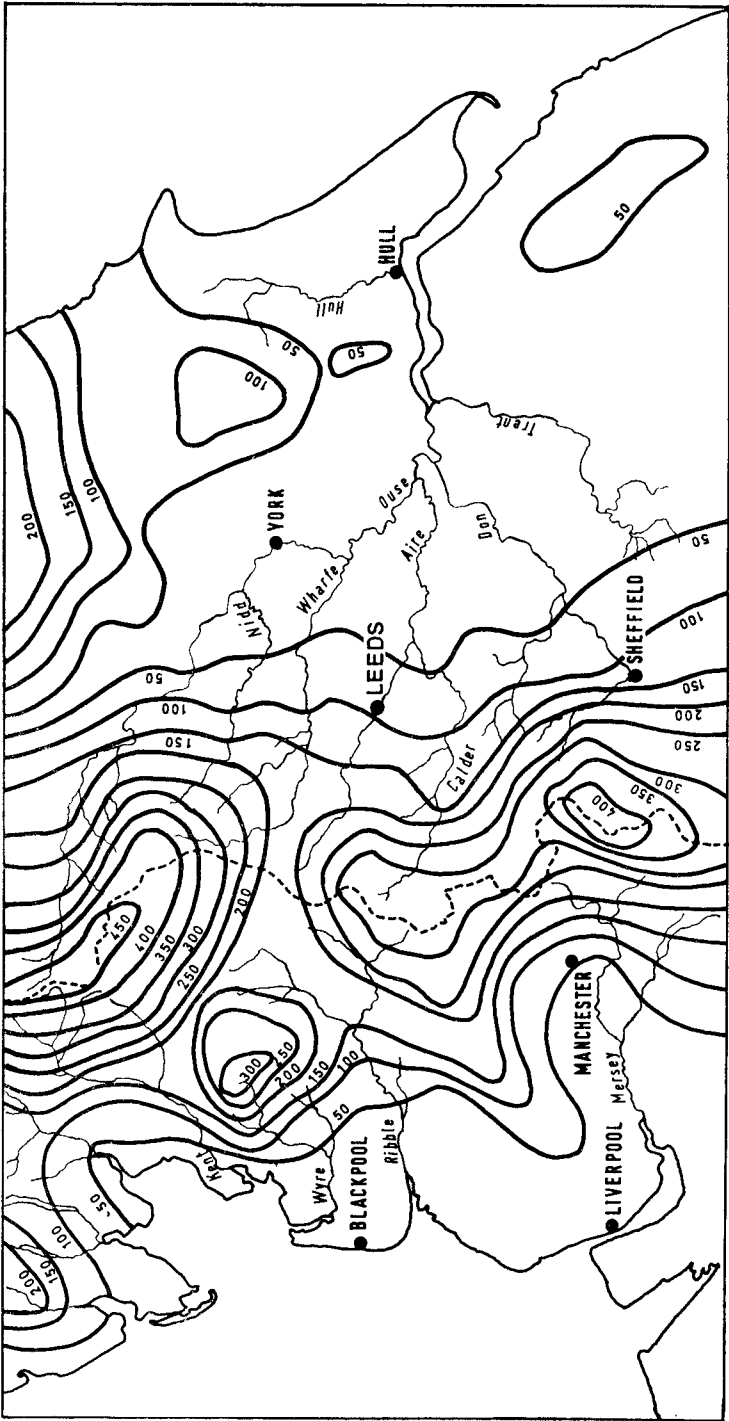


FIGURE 5—MEAN RELIEF MAP (8-km RADIUS) OF PENNINES
Heights are in metres.

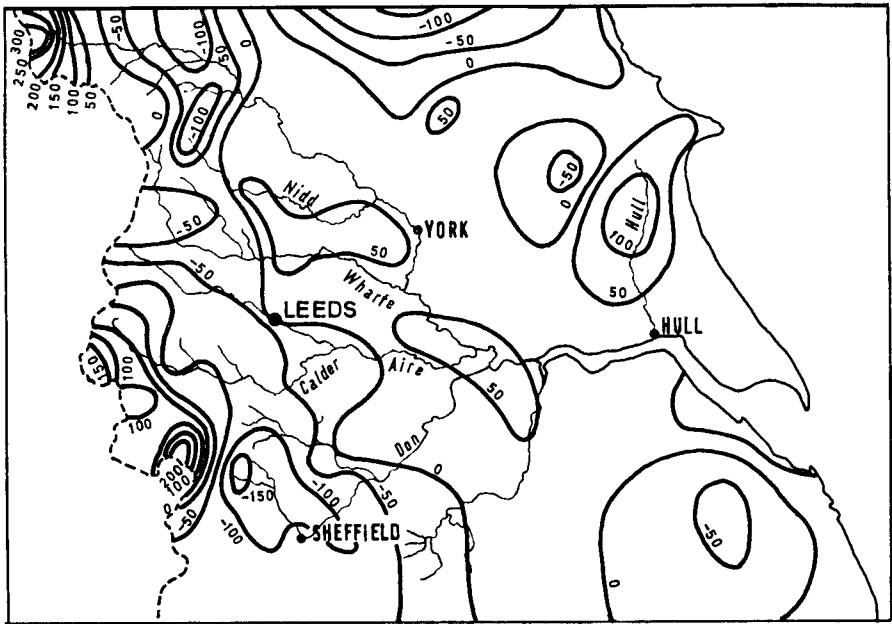


FIGURE 6—DISTRIBUTION OF RESIDUALS BETWEEN OBSERVED AND PREDICTED MEAN ANNUAL RAINFALL (1916-50) OF EAST PENNINES
Rainfall values are in millimetres.

REFERENCES

1. SALTER, M. de CARLE, S.; The rainfall of the British Isles. London, University of London Press, 1921.
2. BRAAK, C.; Klimakunde von Hinterindien und Insulinde. KÖPPEN, W. und GEIGER, R. Handbuch der Klimatologie, Vol. 4, Part R. Berlin, Gebrüder Borntraeger, 1931.
3. DE BOER, H. J.; On the relation between rainfall and altitude in Java, Indonesia. *Chron Nat, Djakarta*, No. 106, 8-9, 1950, pp. 424-427.
4. DALE, W. L.; The rainfall of Malaya, Parts I and II. *J Trop Geog, Singapore*, 13, 1959, pp. 23-37; 14, 1960, pp. 11-28.
5. SPREEN, W. C.; A determination of the effect of topography upon precipitation. *Trans Amer Geophys Union, Washington*, 28, 1947, pp. 285-289.
6. BURNS, J. I.; Small-scale topographic effects on precipitation distribution in San Dimas Experimental Forest. *Trans Amer Geophys Union, Washington*, 34, 1953, pp. 761-767.
7. SCHERMERHORN, V. P.; Topography and annual precipitation. *Wat Resour Res, Washington*, 3, 1967, pp. 707-711.
8. RODDA, J. C.; An objective method for the assessment of areal rainfall amounts. *Weather, London*, 17, 1962, pp. 54-59.
9. UNWIN, D. J.; The areal extension of rainfall records: an alternative model. *J Hydrol, Amsterdam*, 7, 1969, pp. 404-411.
10. BLEASDALE, A. and CHAN, Y. K.; Orographic influences on the distribution of precipitation. Geneva, World Meteorological Organization. Distribution of precipitation in mountainous areas, Vol. II, Geneva, 1972, pp. 322-333.
11. SHAW, ELIZABETH M.; An analysis of the origins of precipitation in Northern England, 1956-1960. *Q J R Met Soc, London*, 88, 1962, pp. 539-547.
12. DUCKSTEIN, L., FOGEL, M. M. and THAMES, J. L.; Elevation effects on rainfall: a stochastic model. *J Hydrol, Amsterdam*, 18, 1973, pp. 21-35.
13. London, Meteorological Office. British Rainfall Supplement, 1961-1965. London, HMSO, 1971.

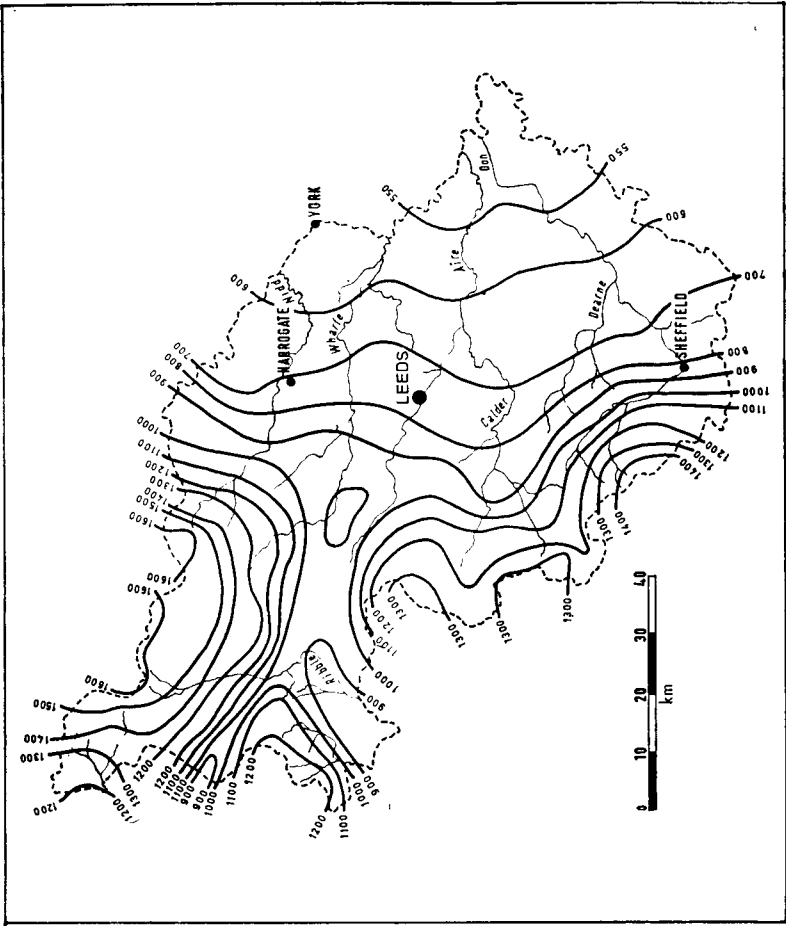


FIGURE 7—MEAN ANNUAL RAINFALL (1916-50) OF WEST YORKSHIRE DERIVED FROM EQUATION (3)
Rainfall values are in millimetres.

A MEMORABLE RAINFALL EVENT OVER SOUTHERN ENGLAND (PART II)*

By PAULINE M. SALTER and C. J. RICHARDS

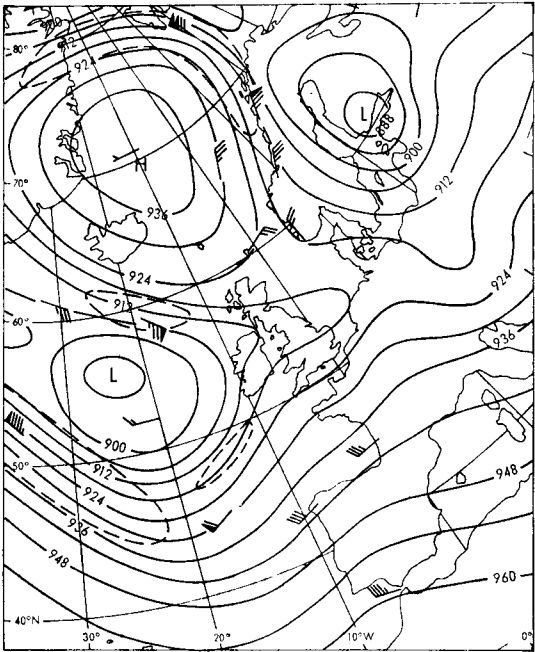
Summary. During the period 14–16 September 1968 parts of southern England experienced a memorably heavy fall of rain and substantial flooding occurred in places. The rain system was particularly intense over the south-east during the 15th. From a meteorological analysis of the situation it appears that the dominant mechanism governing the precipitation over the south-east was a pronounced convergence zone in the lower troposphere, overlaid at upper levels by a strong positive vorticity advection field operating within a narrow zone of marked horizontal wind shear. This system became slow moving on the 15th and within it a low-level inflow of potentially unstable, moisture-laden air is envisaged as leading to the 'dumping' of a heavy fall of rain over a relatively small area.

Analysis of the synoptic situation

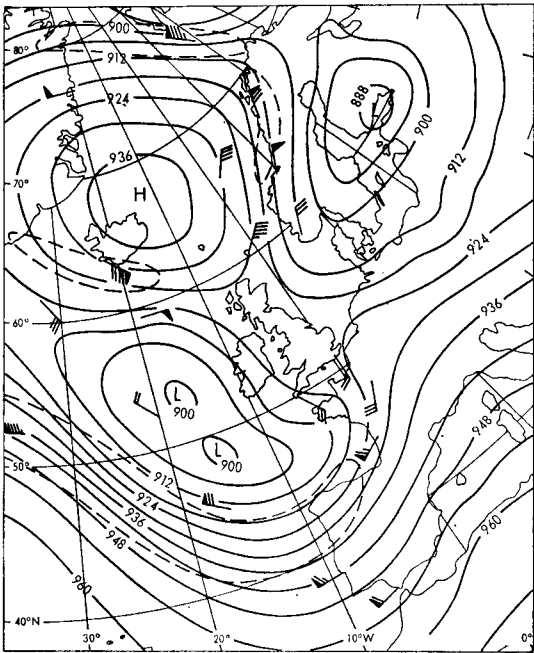
Evolution of the upper flow. The evolution of the upper flow at 300 mb during the period 13–16 September is depicted in Figure 4. During the preceding week western Europe had been dominated by a large blocking upper ridge and by 00 GMT on the 13th a large upper high cell had become cut off in the vicinity of Iceland, with a ridge extending over the North Sea. Large slow-moving upper lows covered the eastern Atlantic and Finland at this time with two well-marked jet streams in evidence. A north-westerly jet was propagating south-eastwards across the central Atlantic towards Portugal, amplifying the upper trough in this region; by 00 GMT on the 14th a considerable fall of contour height had taken place towards Biscay with a major trough becoming established at 10°W. Simultaneously, a strong polar jet round the northern flank of the upper high cell reached Scandinavia as a north-easterly current. A narrow ridge, or anticyclonic col, still covered the British Isles at 00 GMT on the 14th, but during the 14th the north-easterly jet propagated across Scotland, eventually connecting up with the cyclonic circulation around the upper low that had developed over Biscay. At the same time a south-westerly jet was strengthening over Spain and France, ahead of the increasingly confluent long-wave trough in this area. These evolutions effected a dramatic breakdown of the ridge over southern Britain, and by 00 GMT on the 15th a sharp trough had extended from the Biscay vortex across south-east Britain to Scandinavia. This trough remained quasi-stationary for much of the 15th, but by the 16th the Biscay vortex had transferred over northern France, broadening the associated trough appreciably. The south-westerly jet was displaced slowly eastwards over central Europe, whilst developments north of the British Isles cut off the north-easterly flow from Scandinavia.

The 1000–500-mb thickness pattern (Figure 1) reflects the changes in the upper-flow pattern during the period. The amplification of the upper trough near Spain on the 14th is accompanied by a tightening of the thermal gradient there and by the establishment of a marked baroclinic zone over south-west Europe. Cold advection, associated with the propagation of the north-easterly jet across Scotland, had produced a sharp thermal trough between Sweden and northern England by 00 GMT on the 15th. Over south-east England, however, thermal winds were mainly light during the 15th, suggesting that the rain system here was not much of a baroclinic feature, unlike the frontal system

* Part I appeared in the *Meteorological Magazine* for September 1974.



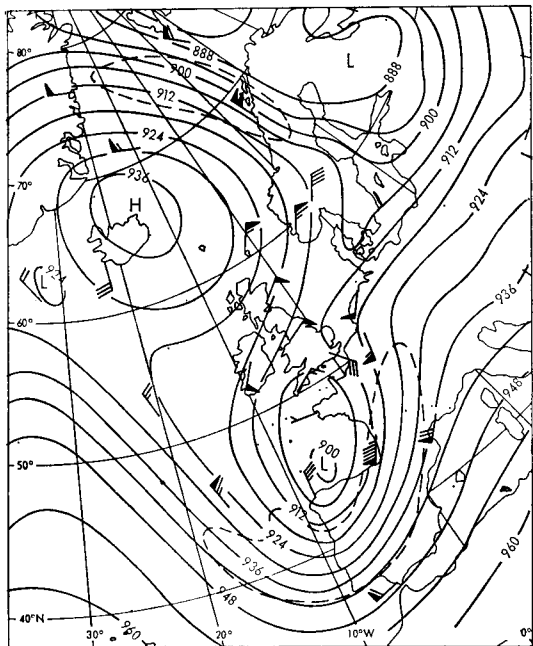
(a) 00 GMT on 13 September



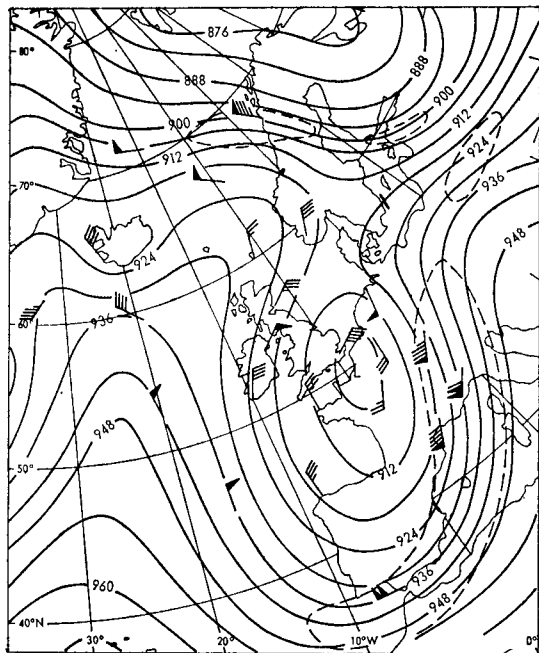
(b) 00 GMT on 14 September

FIGURE 4—300-MILLIBAR CONTOURS, 13-16 SEPTEMBER 1968

Pecked lines denote isotachs enclosing wind speed greater than 75 kt.
Contours are in geopotential decametres.



(c) 00 GMT on 15 September



(d) 00 GMT on 16 September

FIGURE 4—continued

Pecked lines denote isotachs enclosing wind speed greater than 75 kt.
Contours are in geopotential decametres.

over the nearby Continent, which was conspicuously associated with a jet stream aloft.

Several interesting features of the upper-flow pattern during the 14th are highlighted in the photographs taken by the then operational satellite ESSA 6. Figure 5 is a nephanalysis constructed for the area in the vicinity of the British Isles, based on orbits of the satellite between 08 and 12 GMT on the 14th.⁸ The almost occluded vortex of the depression off south-west England is shown, together with its associated band of frontal cloud spiralling in towards the centre of the vortex. A tongue of clearer air, accompanied by open cellular convection, in the rear of the depression, reveals a cold advection field behind the cold front. Within the thermal trough at 10°W an area of enhanced cumulus and cumulonimbus convection is visible at 44°N 12½°W, marking an area where maximum advection of cyclonic vorticity is occurring in the mid and

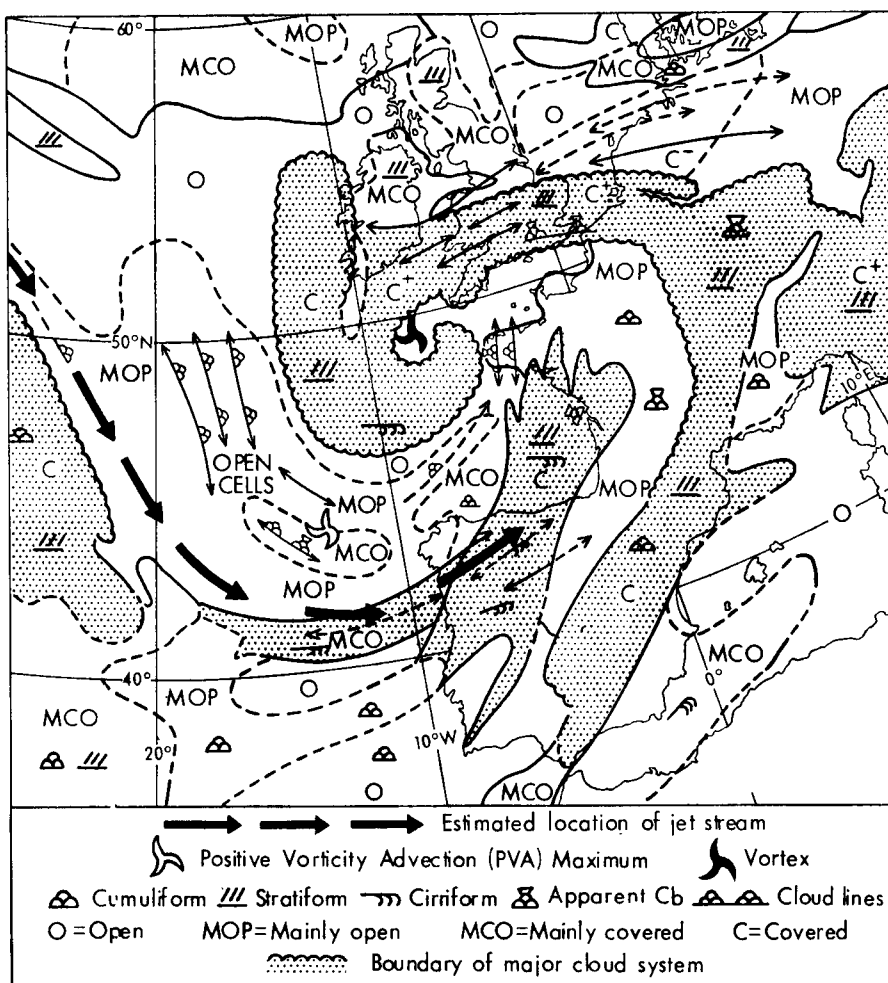


FIGURE 5—NEPHANALYSIS BASED ON CLOUD PHOTOGRAPHS FROM ESSA 6 BETWEEN 08 AND 12 GMT, 14 SEPTEMBER 1968

upper troposphere, associated with general uplift in this region. Of particular significance from the point of view of subsequent developments over northern France later in the day is the large comma-like cloud mass over the Bay of Biscay lying within the cold air mass and detached from the main baroclinic zone further east. This probably represents a much more developed centre of vorticity advection aloft and lies within the left-exit region of the south-westerly jet, then propagating across Spain and France. It reveals substantial ascent through the troposphere. The cloud mass appears stratiform with convective cells embedded in it. Fingers of probably old anvil cirrus (cirrus spissatus cumulonimbogenitus) stretch ahead over western France. Storms were reported over western France later in the afternoon of the 14th. This feature gives a visual indication of the physical and dynamical processes occurring within an area of marked cyclonic vorticity advection aloft which was approaching southern England later on the 14th.

In Figure 1, the 700-mb dew-point depression has been used to map the moisture distribution of the lower troposphere in the vicinity of the British Isles. Of interest is the formation, by the 15th, of a broad area of almost saturated air over south-west Europe which extends across south-east Britain and central Europe south of 55°N by 12 GMT on the 15th. In particular, the south-westerly jet exit region over France on the 14th is dominated by wet air in the lower troposphere.

Tephigram analysis. Figure 6 shows the temperature/dew-point soundings for Crawley between 12 GMT on the 14th and 12 GMT on the 15th. The ascent for

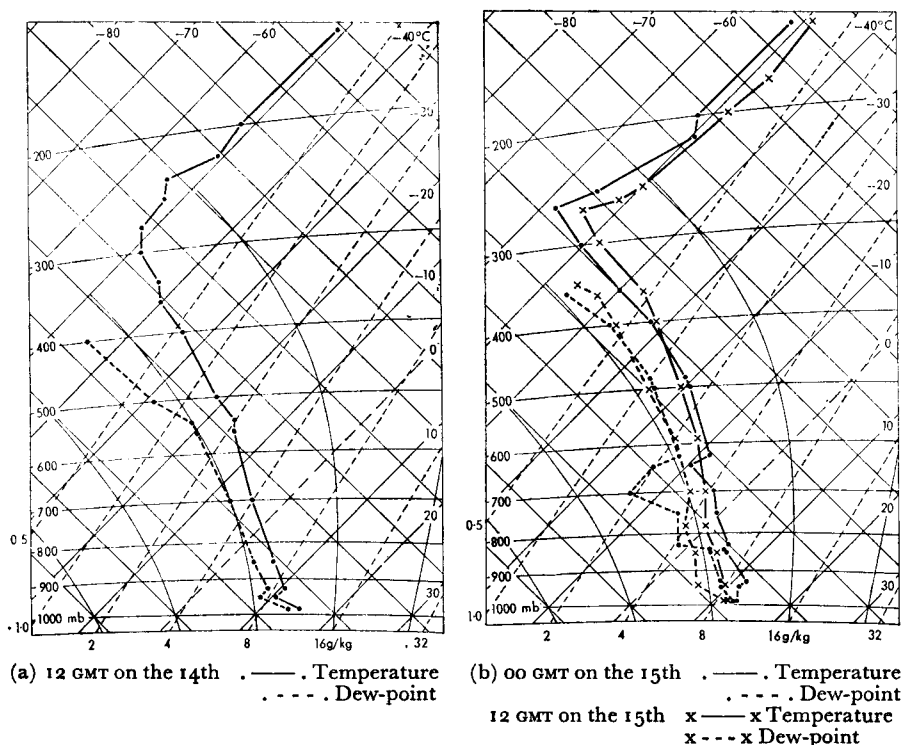


FIGURE 6—CRAWLEY TEPHIGRAMS FOR 14–15 SEPTEMBER 1968

12 GMT on the 14th (Figure 6(a)) reflects the thundery activity associated with the cold occlusion then over southern England. It is highly unstable for surface air, where screen-level wet-bulb potential temperature (θ_w) is around 14 or 15°C. Potential instability is apparent in the lowest layer up to 650 mb, at which level θ_w reaches a minimum of 11°C. With saturation θ_w (θ_s) at upper levels only a little higher, at 13°C, pronounced instability would be readily released through surface heating if not through dynamical uplift within the trough⁴ and this is borne out by the vigorous convection at the time.* Vigorous electrical activity was a noted feature of this initial rain system.

Figure 6(b) (00 GMT on the 15th), shows the structure of the troposphere as it existed over south-east England before the arrival of the second system. It is moist, and though it reveals a more neutral lapse rate than on the previous day, the moist saturated adiabatic profile ($\theta_s = 14^\circ\text{C}$) dominating the upper troposphere is interesting. It reflects the recent cumulonimbus convection of the previous day⁵ and suggests relatively smooth ascent for any low-level air source with θ_w exceeding 14°C, once lifted to saturation. The energy released by the convection depends, however, on the difference between θ_w of the ascending air and θ_s aloft. (Where the adiabatic ascent characteristic of cumulonimbus convection has been in progress aloft, the lapse rate at upper levels tends towards saturated adiabatic.⁵) Surface air over south-east England was too stable to trigger off spontaneous convection during the morning of the 15th, with $\theta_w = 13^\circ\text{C}$, so an external source of potentially unstable air must be discovered.

By 12 GMT on the 15th Crawley was lying near the heart of the convergence zone and a prolonged period of heavy rain and thunderstorms had recently ceased in the area. Though very moist at all levels, the midday ascent is more stable than 12 hours previously, particularly aloft, and this accounts for the weakening of thundery activity earlier reported within the rain system during the morning. A general cooling below 500 mb is also apparent.

The convergence zone and discussion. The convergence zone associated with the surface trough is illustrated in Figure 7 which shows streamlines of surface airflow at 09 GMT on the 15th. Pronounced convergence of air from between north-east and south-east is evident within a narrow belt over south-east England. Both speed convergence, along particular streamlines, and streamline convergence, are marked especially over the Thames Estuary and southern North Sea. This flow pattern would suggest a zone of pronounced uplift in the vicinity of the surface trough.

Trajectories of the airflow at the surface and at 700 mb are depicted in Figure 8, drawn for air converging over south-east England on the morning of the 15th. Figure 8(a) shows 700-mb trajectories, together with the distribution of θ_w at 700 mb at 12 GMT on the 14th. At this level a broad flow of air from the west of Spain crossed France during the 14th, and a branch later reached south-east England from an easterly direction. Except for a tongue of warm air ($\theta_w = 16^\circ\text{C}$) over Belgium, air at 700 mb over France was potentially cold at 12 GMT on the 14th, with θ_w near 12°C, and it would appear that this colder air arrived over south-east England on the morning of the 15th. In

* A layer of air is potentially unstable if θ_w decreases with height through the layer. For instability to be realized this layer must be lifted to saturation. Where mixing effects are minimal, uninhibited adiabatic ascent will follow until a level is reached at which θ_s of the environment exceeds θ_w of the ascending air.

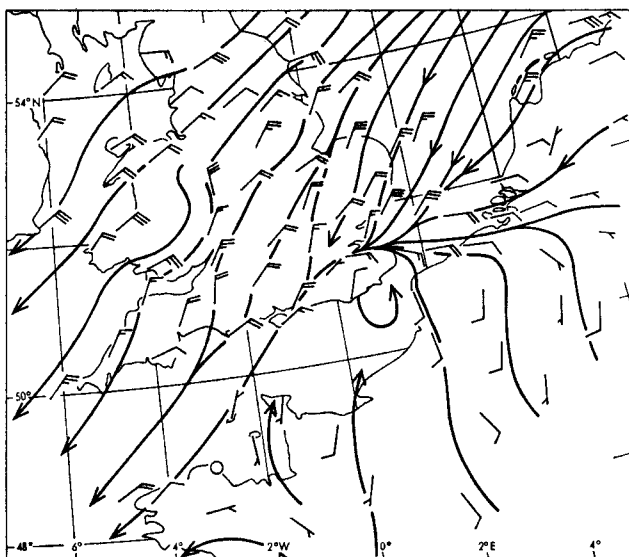


FIGURE 7—STREAMLINES OF SURFACE AIRFLOW AT 09 GMT ON 15 SEPTEMBER 1968

contrast Figure 8(b) shows surface trajectories drawn for air above the friction layer, together with the 1000-mb distribution of θ_w at 12 GMT on the 14th. Superimposed on this is a schematic representation of the 700-mb flow south of the convergence zone. At the surface, the broad, cold north-easterly current north of the convergence zone can be traced back to Finland and western Russia early on the 13th. It appears to present an effective barrier to the warm southerly flow (converging along PP in the diagram). This southerly flow can be divided into two significantly distinct streams, labelled 'A' and 'B' in Figure 8(b) and separated by the line RR. Stream A originated from a moist stagnant air mass over central Europe on the 13th and, with surface θ_w exceeding 16°C throughout a large region by 12 GMT on the 14th, this air was drawn north-westwards into the convergence zone, probably ascending over south-east England within the narrow zone separating PP and RR in this area. Warm air with $\theta_w = 15\text{--}16^\circ\text{C}$ was also present at the surface over the southern North Sea and Thames Estuary on the morning of the 15th. Stream B can be tracked back to the west of Biscay. It was drawn over France during the 14th and represents the air to the south-west of the surface trough. This stream was a little cooler than stream A.

The superimposed 700-mb flow in Figure 8(b) shows that warm, moist air in stream A ($\theta_w = 15\text{--}16^\circ\text{C}$), flowing westwards into the convergence zone in the vicinity of south-east England, was being overridden at 700 mb by a potentially much colder stream ($\theta_w = 12^\circ\text{C}$). The subsequent and substantial potential instability would have been readily released within the ascending branch of stream A. The fact that the upper troposphere over south-east England on the 15th tended towards increasing stability may well have accounted for the prevention of more severe thundery activity than was actually experienced. θ_8 aloft was not far below the general value of θ_w within stream A.

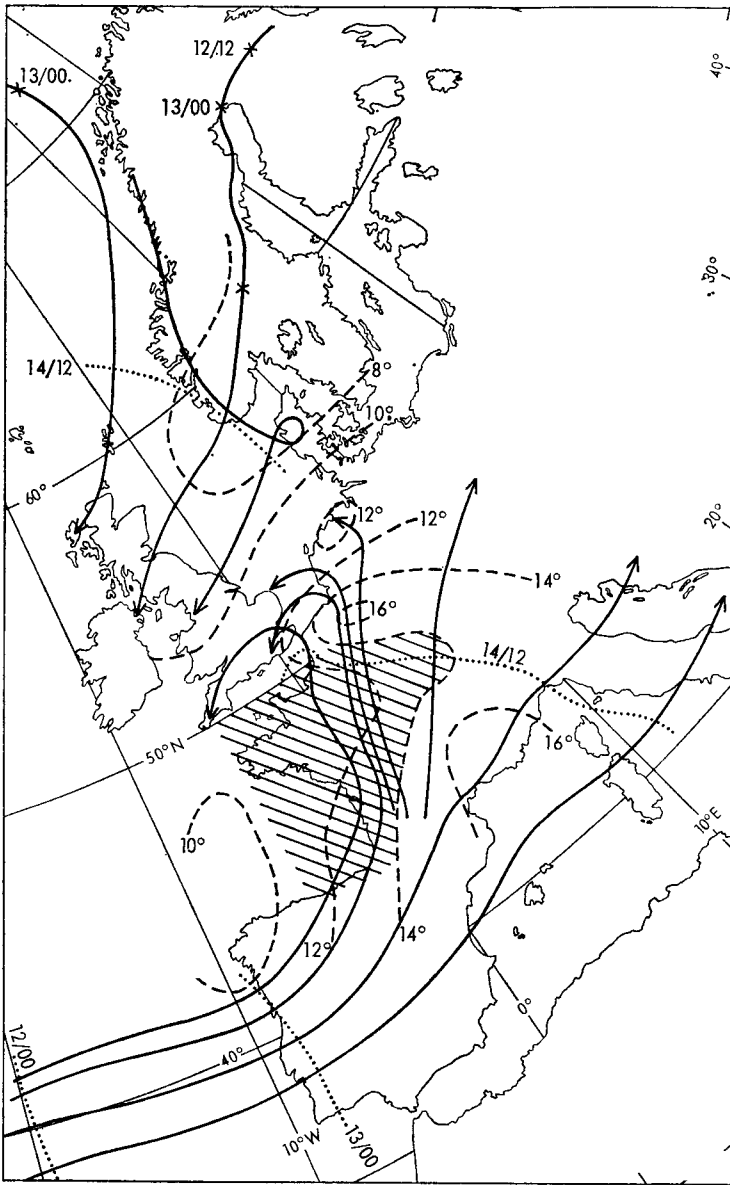


FIGURE 8(a)—700-MILLIBAR AIR TRAJECTORIES UP TO 06 GMT ON 15 SEPTEMBER 1968

Pecked lines are isothermals of θ_w at 700 mb in degrees Celsius at 12 GMT on the 14th. Hatching indicates part of area where $\theta_w < 14^\circ\text{C}$.

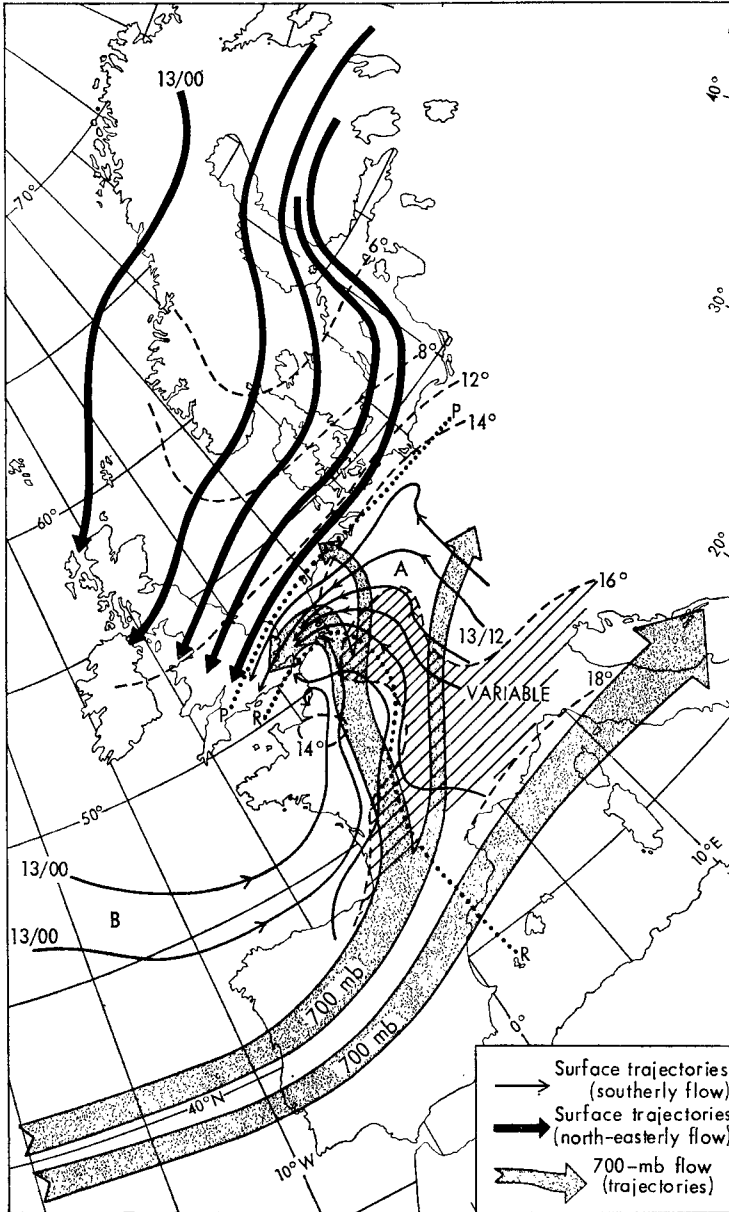


FIGURE 8(b)—SURFACE (GEOSTROPHIC) AIR TRAJECTORIES FROM 00 GMT ON 13 SEPTEMBER TO 09 GMT ON 15 SEPTEMBER 1968

Pecked lines are isothermals of θ_w at 1000 mb in degrees Celsius at 12 GMT on the 14th. Hatching indicates area where $\theta_w > 16^\circ\text{C}$.

Figure 9, which shows the vertical wind shear over Crawley during the 15th, affords separate evidence of a differential thermal advection field within the convergence zone and the principal features of it are summarized schematically in Figure 10. At 00 GMT on the 15th warm advection was in evidence at all levels, concentrated mainly below 800 mb. Figure 9 shows warming from the east below 900 mb by 06 GMT, capped by significant cold advection between 850 and 700 mb (also at about 400 mb).⁶ It will be recalled that the heavy rainfall of the morning began in the Crawley area at about 06 GMT. This wind profile is repeated at 12 GMT, the cooling below 400 mb now being apparent on the midday ascent. At 18 GMT the advection field becomes weak at all levels, reflecting the westward passage of the trough axis over Crawley at about this time. Crawley's wind profile is imitated over Hemsby later on the 15th, though to a lesser degree, and can be associated with the approach of the convergence zone towards East Anglia at this time.

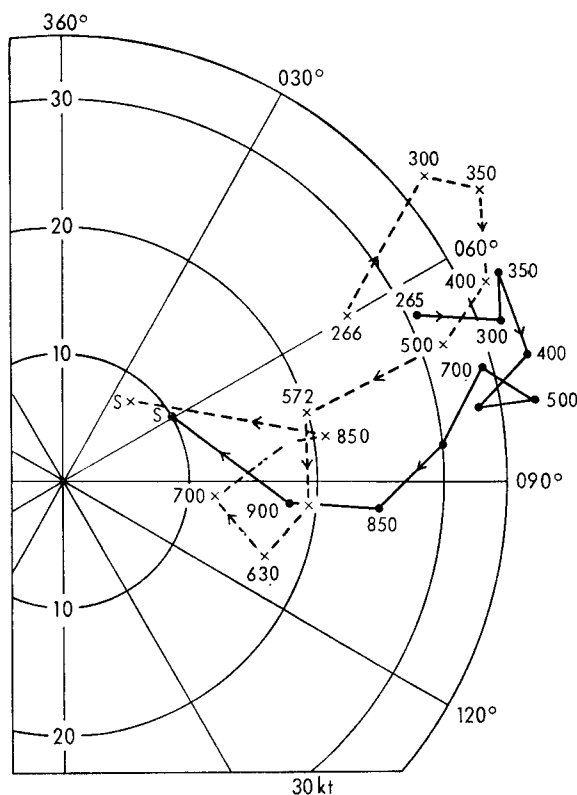


FIGURE 9—HODOGRAPH OF THE VERTICAL WIND PROFILE OVER CRAWLEY ON 15 SEPTEMBER 1968

· — · 06 GMT x - - x 12 GMT

Conclusions. During the analysis of the upper flow, emphasis was placed on the developments that occurred in the vicinity of the British Isles during the 14th and 15th. The propagation of two jet streams effected the breakdown of an upper ridge over the country during the 14th, substituting for it a sharp

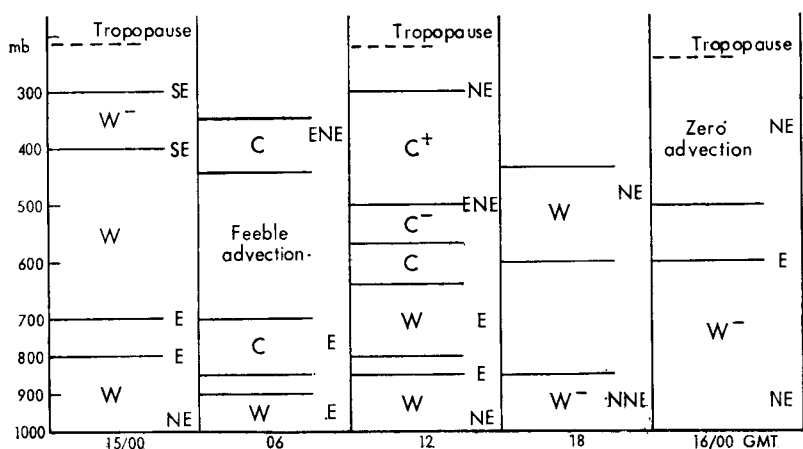


FIGURE 10—THERMAL ADVECTION AND RELATIVE STABILITY ANALYSIS OF THE AIR MASS OVER CRAWLEY ON 15 SEPTEMBER 1968 TAKEN FROM RADIOSONDE AND PILOT WIND DATA

W denotes warm advection, C cold; + and - are relatively strong and relatively weak advection fields respectively. Wind directions are approximate. Lowest C in middle column should read C+.

trough by 00 GMT on the 15th, orientated north-east to south-west across south-east Britain. This trough can be described as a 'shear-zone' that exhibited pronounced horizontal wind shear across its axis, a jet-exit region common to both north-easterly and south-westerly jets in which marked cyclonic vorticity advection was occurring, and a zone where pronounced ascent of air would be expected on purely dynamical grounds. The shear-zone became a stationary feature of the atmosphere for approximately 24 hours. These developments are summarized in Figure 11.

The associated low-level convergence zone was an equally notable feature. A low-level current of warm, moisture-laden air, drawn westwards into the convergence zone, was overridden in the lower middle troposphere by potentially colder air. In an environment already experiencing marked dynamical uplift this potential instability would have been readily released. Throughout the period of continuous heavy rainfall, the vertical wind profile of radiosonde ascents independently revealed the presence of a differential thermal advection field in the lower troposphere. The intensity of convection was probably limited by the small depression of θ_s aloft over south-east England relative to θ_w of the inflowing warm low-level air. The rainfall distribution shown in Figure 3 silhouettes vividly the influence of the surface convergence zone. The axis of the heaviest precipitation virtually coincides with that of the convergence zone when it became slow moving during the morning and afternoon of the 15th. The isohyet gradient on the south of this zone is particularly pronounced in places. As the shear-zone weakened by the 16th, the dynamical mechanism described above disappeared. Precipitation thus ceased to be as heavy or as organized as it had been on the 15th.

Several factors that are regarded as meteorologically significant have been discussed. The rainfall event was characterized by the coincidence of these

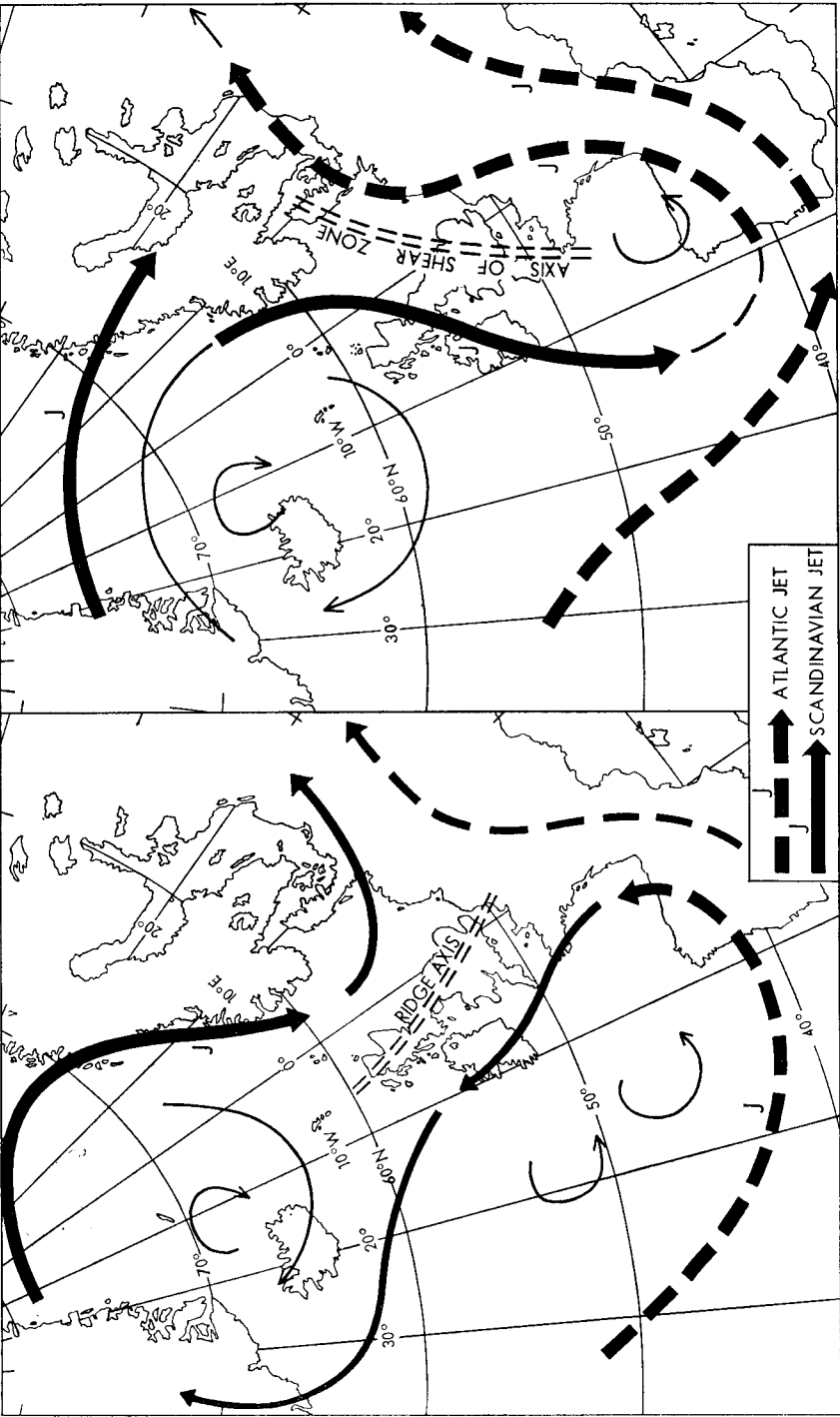


FIGURE 11—EVOLUTION OF THE UPPER FLOW PATTERN NEAR THE BRITISH ISLES,
14-15 SEPTEMBER 1968
(a) 00 GMT on the 14th (b) 00 GMT on the 15th

factors, each of which isolated out of context, would not be considered exceptional. However, the strong cyclonic vorticity advection field operating within the shear-zone aloft must be regarded as the controlling influence. Other factors must be viewed in this context, in which a quasi-stationary system allowed the dumping of a substantial fall of rain over a relatively small area, an area almost of mesoscale dimensions.

Acknowledgments. The authors are indebted to the River Authorities named in the text, to the Thames and Lee Conservancies, and to the Greater London Council, for information supplied about flooding and damage in their areas.

REFERENCES

3. ANDERSON, R. K. *et alii*; Application of meteorological satellite data in analysis and forecasting. Washington, D.C., U.S. Department of Commerce, ESSA Technical Report NES-51, 1969.
4. London, Meteorological Office. Handbook of weather forecasting, Vol I. London, HMSO, 1964, Chapter 3, p. 20.
5. CARLSON, T. N. and LUDLAM, F. H.; Large-scale conditions for the occurrence of severe local storms. *London, Imp Coll Sci Tech, Dep Met, A Summ Rep No. 1* (Grant AF EOAR 64-60), 1965, pp. 1-74.
6. London, Meteorological Office. Handbook of weather forecasting, Vol. I, 1964, Chapter 3, pp. 4-9. (Unpublished, copy available in the Meteorological Office Library, Bracknell).

551.510.42: 551.510.522: 551.584.5 (495)

A NOTE ON AN INDEX OF TRAPPING EFFICIENCY OF SMOKE PARTICLES IN THE LAYER SURFACE TO 1000 MILLIBARS OVER ATHENS AT NIGHT

By JOHN G. DIKAIKOS

Climatological Laboratory of the University of Athens

Summary. An index is proposed of 'the mean monthly trapping efficiency of smoke particles in the layer surface to 1000 millibars over Athens at night'. The index may readily be calculated from readings at the surface and 1000 mb. Smoothed mean monthly values of the index and of the nocturnal concentration of smoke particles show close agreement.

Introduction. Measurements of air pollution giving mean concentrations of smoke particles in $\mu\text{g}/\text{m}^3$ were made by the National Meteorological Institute of Athens (NMIA) on almost all nights in 1971 between 22 and 06 GMT (00-08 Local Mean Time). The measurements were made at the NMIA on top of Nymphe's hill (107 m above mean sea level) which lies almost in the centre of Athens and is surrounded by roads carrying a great deal of traffic. This point lay under or close to 1000 mb throughout the period and the measurements are expected to be representative of the layer under discussion.

For all practical purposes the smoke particles may be considered to originate from buses and cars. The number of these vehicles and hence the emission of smoke do not change significantly from month to month.

The night-time wind blows from varying directions with very low speeds. Mean monthly values varied during 1971 from 4.63 m/s to 1.56 m/s with a mean annual wind speed of 3.17 m/s. The layer from the surface to 1000 mb was on average stable with positive vertical gradients for all mean monthly values of potential temperature.

The average monthly degree of pollution is expected to depend mainly on the average monthly rate of upward transport of smoke particles through the

layer and consequently upon the average monthly values of both potential temperature and the vertical gradient of wind speed within the layer.

With these considerations in mind an index was sought, expressed in terms of the above gradients, which would measure the 'trapping efficiency' and which would be strongly and positively correlated with the degree of air pollution.

The index. Mean monthly values of the index are symbolized by δ_i ($i = 1$ for January, 2 for February, ... 12 for December) and are calculated as follows:

$$\delta_i = 10^2 \times k_1^{-1} (\overline{\Delta\theta/h})_i (\overline{\Delta u/h})_i^{-1} \quad (\text{s m}^{-1} \text{ deg C}^{-1}) \quad \dots (1)$$

where

$$k_1 = \frac{1}{n_1} \sum_{j=1}^{n_1} (t_{1000} + t_s)_j (\theta_{1000} + \theta_s)_j / 4 \quad (\text{deg C K}) \quad \dots (2)$$

$$(\overline{\Delta\theta/h})_i = \frac{1}{n_1} \sum_{j=1}^{n_1} (\theta_{1000} - \theta_s)_j / h_j \quad (\text{K m}^{-1}) \quad \dots (3)$$

$$(\overline{\Delta u/h})_i = \frac{1}{n_1} \sum_{j=1}^{n_1} (u_{1000} - u_s)_j / h_j \quad (\text{s}^{-1}) \quad \dots (4)$$

and

t is temperature in degrees Celsius,

θ is potential temperature in kelvins,

u is wind speed in metres per second,

h is depth of the layer, surface to 1000 mb.

Subscripts s and 1000 indicate the values at the surface and at 1000 mb respectively; n_1 is the monthly number of air-pollution measurements and radiosonde ascents (made at Hellinikon, about 10 kilometres from NMIA), and j takes the values 1, 2, ... n_1 .

The mean monthly degree of air pollution in the layer is calculated from:

$$N_1 = \frac{1}{n_1} \sum_{j=1}^{n_1} N_j \quad (\mu\text{g/m}^3) \quad \dots (5)$$

where N_j is the mean nightly concentration of smoke particles.

Presentation of data and discussion. Table I gives the values of δ_i and N_1 calculated from equations 1-5, after being smoothed by the formula:

$$\bar{x}_1 = (x_{1-1} + x_1 + x_{1+1})/3 \quad \dots (6)$$

where as before x_1 denotes January, x_2 February ... x_{12} December and $x_{13} = x_1$.

Figure 1 shows the graphs of these smoothed means. There is a close similarity between the curves, the minimum of both falling in August, with a secondary

minimum in February. The maximum for $\bar{\delta}_1$ occurs in December and that for $\bar{N}_1$ in November with secondary maxima in April and May respectively.

From Figure 2 it is seen that the points $\bar{\delta}_1$ and $\bar{N}_1$ are closely approximated by the line of least squares fit:

$$\bar{N}_1 = 38.53 + 6.89 \bar{\delta}_1.$$

The correlation coefficient between $\bar{N}_1$ and $\bar{\delta}_1$ has the very high value of +0.94.

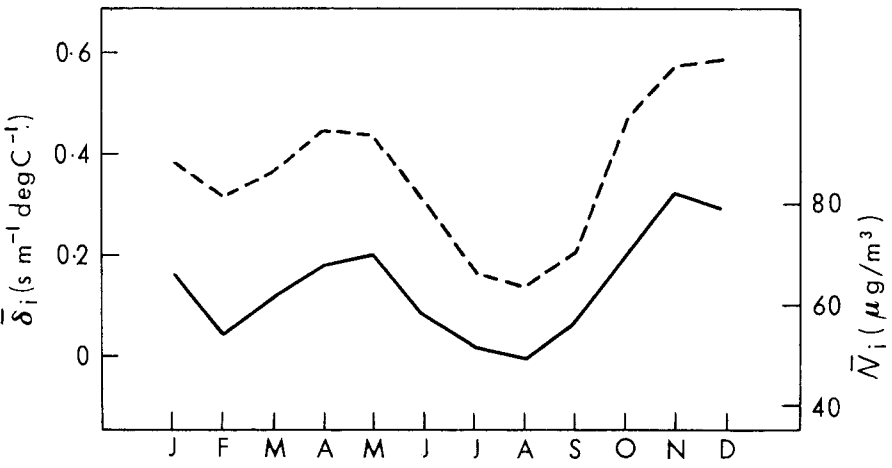


FIGURE 1—ANNUAL CYCLES OF $\bar{\delta}_1$ (---) AND $\bar{N}_1$ (—)

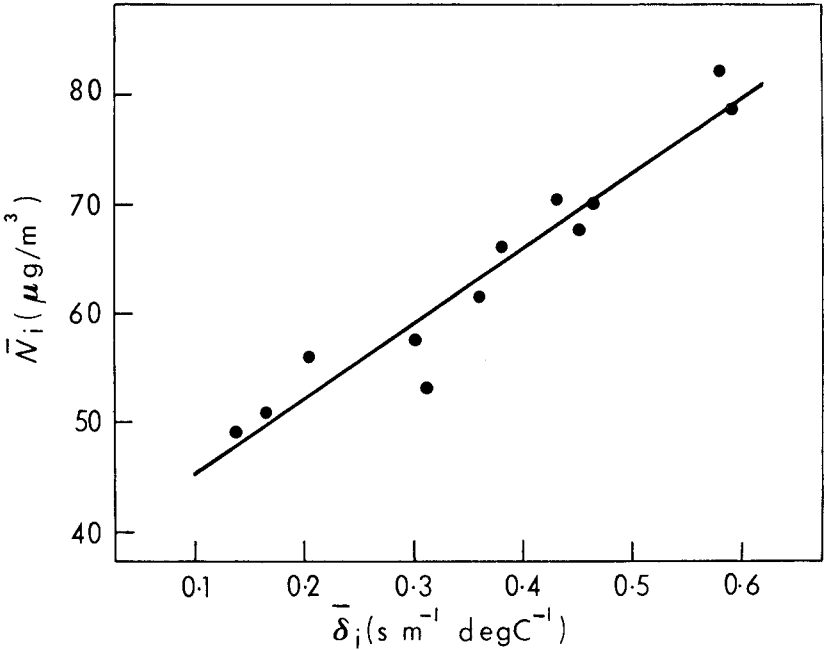


FIGURE 2— $\bar{N}_1$ AGAINST $\bar{\delta}_1$

TABLE 1—VALUES OF $\bar{\delta}_1$ (s m⁻¹ degC⁻¹) AND $\bar{N}_1$ (μg/m³)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
$\bar{\delta}_1$	0.384	0.312	0.362	0.447	0.434	0.304	0.167	0.137	0.205	0.466	0.580	0.591
$\bar{N}_1$	66.2	53.4	61.6	67.8	70.1	57.8	51.2	49.0	56.6	69.8	82.6	79.1

Conclusions. Although the index is based upon radiosonde data made once nightly at Hellinikon Airport two hours after midnight, it gives a good measure of the trapping efficiency of smoke particles, and it is hoped that it will prove a useful tool in dealing with the problems of air pollution in Athens at night.

Acknowledgement. The author wishes to express his deep thanks to Professor L. N. Carapiperis who supplied him with the measurements of air pollution made at NMIA.

BIBLIOGRAPHY

1. DIKAIAKOS, J. G.; Relation between degree of night-time pollution of the air by particles of smoke in Athens and parameters of thermohydrodynamical structure of an air surface layer model. *Pract Acad Athens, Athens*, 48, 1973.
2. SHEPPARD, F. A.; Transfer across the earth's surface and through the air above. *Q J R Met Soc, London*, 84, 1958, pp. 205–224.

MR F. J. PARSONS, M.B.E., COMPLETES 60 YEARS OF OBSERVING

Mr F. J. Parsons, the meteorological observer at the County Observatory, Ross-on-Wye, completed his 60th year as a meteorological observer in July 1974. Mr Parsons commenced his duties at the Observatory in July 1914 and, apart from absence on war service during the First World War, has personally maintained, without a break, a programme of meteorological observations and summaries for the Observatory.

A ceremony to mark the completion of a century of weather observations at the station was held on 17 July 1959. This ceremony was presided over by the Chairman of the Urban District Council. Those attending included the Lord Lieutenant of Herefordshire and representatives from the Royal Meteorological Society, the Meteorological Office and local authorities. A number of former and contemporary assistant observers were also present.

Mr Parsons completed 50 years as an observer in July 1964 and a letter of congratulations was sent to him by Sir Graham Sutton, the then Director-General of the Meteorological Office. In June 1965 the M.B.E. was bestowed by Her Majesty the Queen in recognition of his long and valuable service.

His enthusiasm has ensured for Ross-on-Wye a series of weather records, the excellence of which is equalled at few places in the British Isles, and which is of great value both to the World Meteorological Organization and to the local agricultural community. The high reputation of the Observatory has led to its being classed as a key climatological station of the Meteorological Office, and in 1966 it was adopted as a Reference Climatological Station of the World Meteorological Organization.

Mr Parsons celebrated his 83rd birthday on 14 July 1974.

LETTER TO THE EDITOR

551.591.36

Note on errors that may be induced by using visibility observations taken at greater than hourly intervals

In their paper in the *Meteorological Magazine* for April 1974 Messrs Hinz and Carroll remark at the foot of page 106 that 'Shellard's comment that "very satisfactory estimates of annual frequency can be obtained by using observations made at 0300, 0900, 1500 and 2100 GMT" must be evaluated in the of light what is "very satisfactory" '. This seems hardly a fair comment because the authors have quoted only a part of my table, namely that concerned with very low visibilities (where the samples are small) to which my statement was certainly not intended to apply in isolation.

The figures in Hinz and Carroll's Table I are in fact in very good agreement with those given in my 1959 paper in showing that for visibilities greater than about 50 yards the estimates based on three-hourly, or six-hourly observations are very close to those based on hourly observations.

Incidentally there is a mistake in the heading to column 4 of the table near the bottom of p. 106 of Hinz and Carroll's paper where 'Three-hour' should read 'Six-hour'.

H. C. SHELLARD

*Meteorological Office,
Bracknell.*

OBITUARY

It is with regret that we have to record the untimely death on 26 July of Mr G. F. Trowell, who has regularly taken climate observations for the past 25 years at East Malling Research Station under the Agrometeorological Scheme.

His intelligent interest in weather recording has been demonstrated in his published papers on various aspects of the climate of East Malling.

CORRECTION

Meteorological Magazine, April 1974, p. 106. In the short table at the foot of the page, the heading 'Three-hour observations' should read 'Six-hour observations'.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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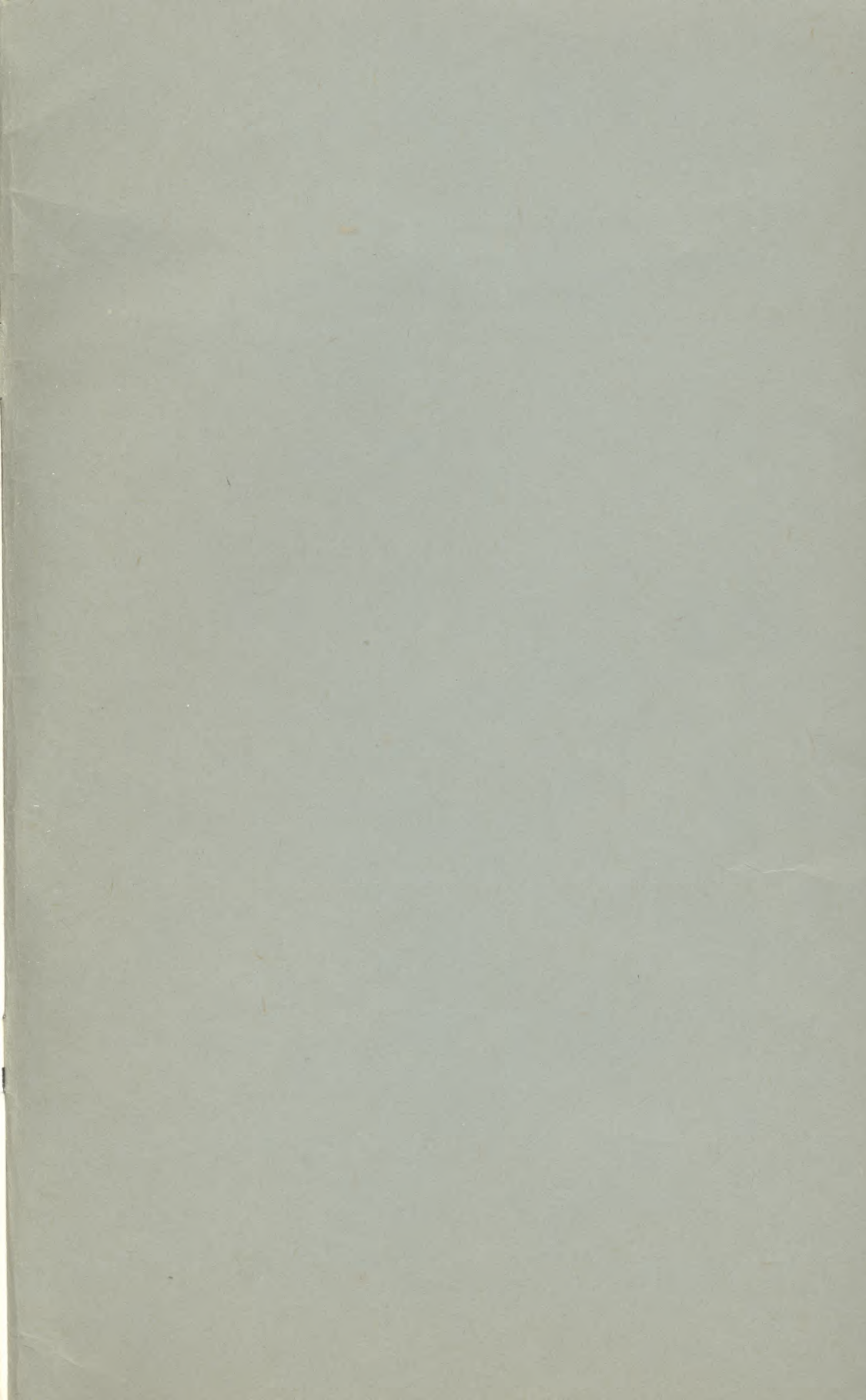
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METEOROLOGICAL OFFICE

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**The Senior Meteorological Officer,
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REPORT AND COMMENTARY ON A SYMPOSIUM ON THE ASSESSMENT AND VERIFICATION OF STATISTICAL AND OTHER SOFTWARE, HELD AT IMPERIAL COLLEGE, LONDON ON 19 DECEMBER 1973

By J. M. CRADDOCK

Summary. The views of several experts on the assessment and validation of computer software are summarized, with comments on their application to meteorology. A selective library of numerical algorithms, improved methods for program development, and an exchange of information on the computing problems of individual groups of meteorologists are suggested as topics worth following up.

Introduction. On 19 December 1973 I attended a Symposium held under the joint auspices of the Royal Statistical Society and the British Computer Society on the Assessment and Verification of Statistical and other Scientific Software, and organized by Dr John Nelder, Head of the Statistics Department at Rothamsted Experimental Station. The discussions produced many points of interest to meteorologists who have to cope with software problems, and enough useful leads to justify the publication of a report on the Symposium in a meteorological journal. I have tried first to give a fair report on the proceedings, and then to suggest lines which sooner or later should result in more useful work being done in less time.

The Symposium. The Symposium was chaired by Mr W. Buckland, of the Economics Intelligence Unit, and was attended by about 200 people, including members of both sponsoring Societies, the universities, the Government Service, and industry. It lasted from 10.30 a.m. to 4.30 p.m. with breaks for lunch and tea, and consisted of four invited contributions, taken in pairs, followed by a Panel discussion. In view of the industrial troubles on the railways, which could have prevented some participants from getting home, the sessions were kept to a strict time-table, which meant that some of the contributions had to be shortened.

After the Chairman's opening remarks, Dr J. Nelder, introducing the main business by speaking on 'A user's guide to the evaluation of packages and systems', stressed the importance of having a proper description which the

customer could consider and assess before deciding whether to buy. With systems, there are three main dangers:

- (a) The system may not do what the description says.
- (b) It may be capable of misuse in the hands of customers who treat it as a 'black box'.
- (c) It may in practice force the user to apply unsuitable methods of analysis to his data.

As speaker, Dr Nelder's task was to arm the user to ask awkward questions of the right people. One question to settle is how the system is driven. A system can be one of two kinds, namely (a) a *translation* system, in which the user's source coding, written in a problem-orientated language, is translated into a universal language (such as FORTRAN or ALGOL), the result being compiled and link-edited with the main coding of the package to produce the object code which the computer will obey, or (b) an *interpretative* system, in which the user's coding in the problem-orientated language remains in being in the computer during run time, albeit in a somewhat modified form, the orders being recognized and interpreted before being carried out by means of the main coding provided by the system. There is something to be said for both types, but GENSTAT, which is Dr Nelder's main contribution to the subject, is an interpretative language. (*Author's note.* The Systems Development Branch of the Meteorological Office has a copy of the GENSTAT documentation, with examples, obtained from the Edinburgh Computing Centre, which deals with its implementation for IBM machines. Users of ICL machines should refer to Rothamsted Experimental Station.) After the question of the preferred type of language has been considered, the question of extensibility comes next. Some means by which the user can extend the system either temporarily or permanently is essential. Facilities for branching, which allow the user to vary the course of the computation, or to repeat certain sections, are also necessary.

After extensibility and branching facilities, the next point to examine is the treatment of data structures. What types of structure can be handled by the system, and how are they treated? Most systems provide for the rectangular matrix, which is the most important, but others are also useful.

In agricultural problems, rows correspond to the data for one case, which may be of several kinds, e.g. numerical measurements, integer variables, and qualitative variables or classifications, while columns consist of values of one variable for different cases. The main advantage of storage by columns is that since the items in columns are all of one kind, they can often be packed more closely than is possible with storage by rows. However, storage by rows is generally preferable, and in GENSTAT the ability to manipulate data in columns when desired is provided by allowing several consecutive rows of the matrix to be worked on at the same time.

After the data structures, the algorithms of the system should be examined, and answers obtained to the questions, 'Do they work?' and 'Do they do what is wanted?' In particular, the treatment of missing and incredible observations should be considered, since, for example, one wrong observation in the data used for a regression analysis may produce a ridiculous result.

On the question of documentation, Dr Nelder stressed the importance of documentation at several levels. (The GENSTAT documentation includes a

manual, many illustrative examples, instructions for whoever is running the program, and some training instructions for users.)

Dr J. Larmouth, Senior Systems Programmer at the Cambridge University Computer Centre, then spoke on 'Validating programs'. His advice, as summarized in a hand-out which included a small test program, is:

- (a) Choose the language carefully and read the standard.
- (b) Put all documents, including the preliminary design concepts which you have before getting down to detail, in machine-readable form, as these are likely to be lost sight of as the system develops.
- (c) Make more remarks about global information than about local information.
- (d) Make formal remarks rather than informal, and structure the comment.
- (e) Carry out random testing, e.g. on numbers produced by a random-number generator, but keep and distribute the data and the results.
- (f) Carry out complete testing, going along each path from every possible branching point, and keep the data and results. It may happen that some paths from some points cannot be traversed in any circumstances, and can be omitted without loss.
- (g) Add to the comments when editing. Keep cross-references up to date.
- (h) When producing a version of the system for another computer, generate a copy of the existing version, of which the virtues and vices are known. Do not produce an edited version which may misbehave in some completely novel way.

Dr Larmouth then examined his test program, and showed that it can be proved correct, in the same way that a theorem in Euclidean geometry can be proved.

In the discussion Mr I. D. Hill (Medical Research Council) remarked that Dr Larmouth's test program would not compile in the form printed, and he and various other speakers cast doubt on the practicability of 'complete' testing. Mr Craddock said that although 'correctness' in Dr Larmouth's sense was a virtue in a program, it was neither a necessary nor a sufficient condition for the program being the most suitable for a given job. If a job is being repeated regularly, so that any result which falls outside the usual pattern is immediately suspect, a simple program which gets the right answers 99 per cent of the time may be more effective than a more elaborate one which rarely fails, but which takes up more space or time. Certainly, if provision is made for the abnormal situation, such as coincident eigenvalues, then the coding should be tucked away in a drum segment from which it can be fetched when required, and not kept permanently in core. To Dr Nelder he suggested that besides the questions given, the user should, with reference to the space required by the system, also ask:

- (a) What is the total space needed for the coding?
- (b) How is this divided between administrative coding, which would be required equally in a system with some quite different purpose, and executive coding, which has a recognizably statistical content?
- (c) How readily can the coding be segmented to suit the individual computer?

- (d) How readily can the system be dismantled to get at the few per cent which seems likely to be useful in a new environment?
- (e) How can the coding be interfaced with the customer's own software?

Dr Nelder replied that space requirements were important, and that, given more time, he would have dealt with them. In answer to the last point he said that the best way to interface with the GENSTAT system is to 'output' the data from the meteorological or other software in a form which GENSTAT will accept as input. There should be no great difficulty in doing this. (On reading the GENSTAT literature since the Symposium, I am sure that Dr Nelder is right. GENSTAT is not really adapted for run-of-the-mill meteorological data processing, whereas any meteorologist who wishes to experiment with any of the advanced statistical techniques which it provides should consider whether he can use it. It may easily save him the most frustrating part of his task.)

Mr G. B. Hey (Co-operative Insurance Co. Ltd) said that the methods of validation discussed by Dr Larmouth showed no change from those which he had used, when working with the late L. J. Comrie in 1935, for verifying complicated plugboards on Hollerith machines. In commercial work which involved receipts and payments, and legal obligations, accuracy under every set of circumstances which could arise in real life was most important, and was very rarely achieved, in computer software supplied either by manufacturers or by others. His Company maintained a special test file for use with any new software, which had to reproduce results known from previous analyses before the software was passed as fit for use.

After lunch Mr B. J. Ritchie (Staff Manager, Computer Analysis and Programmers (Reading) Ltd) spoke on 'The verification of complex scientific packages', with reference to a package recently completed for testing an airframe without destroying it, by the application of computer-controlled stresses by means of hydraulic jacks placed against various points in the frame. He said that methods of *proving* the correctness of programs are still in their infancy and are applicable only to logically trivial problems. Today's software professionals therefore adopt the less formal but equally rigorous approach of *testing* their products against predefined criteria dependent upon the application itself. This approach requires that programs be structured in ways which permit the use of software *test tools* throughout all stages of development, and the cost of producing these tools may form an important fraction of the total cost of the software. Great emphasis is placed on building *robust* systems, in which hardware or software failures must be localized. The conceptual planning stage, in which the system is outlined before any detailed coding takes place, is most important and cannot be hurried. 'You cannot produce a baby in one month by putting nine women on the job'.

Dr Brian Ford, Chairman of the Numerical Algorithms Group Project, Oxford University Computing Laboratory, then spoke on 'The assessment and verification of software for a general-purpose numerical algorithm library'. He said that the library was intended for the general users of a university computing laboratory, and that unlike many such projects which set out to include every example of coding published, the Numerical Algorithms Group Project intended to be selective, and to keep only a few of the best programs suitable for dealing with specific problems on computers of all the types likely to be

used. They had a library of about 250 programs covering most aspects of numerical analysis, with the exception of the solution of partial-differential equations, for which they had no suitable contacts. These programs were being tested or adapted for six different types of computer, and as far as possible, common standards of accuracy and documentation were maintained for each type of computer. The programs were issued in semi-compiled form, being copies from the master source file, and information on any failures was to be fed back to the group, who would be responsible for analysing the failures and correcting the master file. They had a precisely specified subset of FORTRAN, which, as far as was known, was interpreted in the same way on all the types of computer. They hope to distribute tested mathematical software, with information on:

- (a) Algorithm performance, from the point of view of
 - (1) Elementary arithmetic.
 - (2) Function evaluation.
 - (3) Function approximation.
- (b) Robustness.
- (c) Numerical stability.
- (d) Speed.
- (e) Region of effectiveness.
- (f) Efficiency.
- (g) Portability.

Some algorithms are contributed by members of the group, while others are produced at the centre. Of the contributed algorithms, not one has produced the same identical answers under test on each of the six families of computer. Differences between answers can arise if the algorithm is unstable or if the problem is ill-conditioned, and differences between families of computer can arise through differences in the input data, or in the conversion from decimal to binary, or in the round-off. The coding itself could conform to one of three standards: coding with redundancy, coding without redundancy, and structural programming, as conceived by Professor Dijkstra.

In the discussion on these papers Mr Craddock remarked that as the Meteorological Office IBM 360/195 computer spent a large part of its working life solving partial-differential equations, there must be scientists within the Office with the know-how needed to fill some of Dr Ford's gaps in this field. On the other hand a selection of algorithms which have been chosen by experts on topics outside meteorology, and which can be obtained when required, could be most useful to any meteorologist wishing to venture outside his own field. He therefore asked:

- (a) Has the Numerical Algorithms Group a specification for its Universal FORTRAN?
- (b) Is there any document giving the address and full description of the group?
- (c) Is there a list of the algorithms tested so far?
- (d) Is there a subscription for joining the group?

In reply, Dr Ford said that so far they had not quite reached the stage of organization implied by these questions, but that they were always willing to discuss the software with scientists concerned with the subject. A lively discussion followed.

After the tea break, a Panel which included the main speakers answered questions propounded by the audience, or by themselves. While the discussion cannot be reported in detail, the following are some of the main points:

Dr Larmouth said that despite appearances, verification techniques *had* advanced since the 1930s. In the discussion on this subject, it appeared that nobody was very enthusiastic about the prospects of proving programs correct by logical process, as opposed to checking their performance by applying them to previously analysed test data.

The question of the transferability of programs was raised, and there was some good-humoured banter about whether Cooper's ASCOP (A statistical computer procedure) was worth the fee asked for it by the National Computer Centre. The answer seems to depend on whether the prospective purchaser expects to use nearly all the system, or only a small part.

Mr I. D. Hill mentioned that the efficiency of the object program produced from a high-level source program depended to a considerable extent on the compiler used, but the subject was not taken up.

The problem of keeping track of a computation while developing complicated software was raised, and Mr Craddock remarked that for any computer with the DEBUG feature provided by the IBM FORTRAN G compiler, an efficient solution consists in having a special integer variable, e.g. JEST, which is used purely for tracking and diagnostic purposes. When the DEBUG feature is in use for this variable, any assignment statement such as `JEST = 999`, `JEST = NZ(73)` produces a diagnostic print `JEST =` (the numerical value assigned) every time the statement is executed. The rules to be followed in using the JEST variable are simply that no statement including JEST is ever labelled, and that no two assignment statements give the same value to JEST. Thus each printed value of JEST is positive proof that the computation has reached a particular point, and if the tracking assignment statement is followed either by a WRITE statement for some interesting array, or by an assignment setting JEST equal to some interesting variable, the computation can be followed to the desired depth without the production of quantities of meaningless paper. When the testing is complete, all statements involving the JEST variable can be removed without affecting the rest of the computation, except by making it marginally faster. Mr Craddock said that the device is so easy and flexible that since finding it he has hardly used any other, and inquired whether computers of other manufacture had anything equivalent to the DEBUG feature. The question was left unanswered.

The question of documentation was discussed at some length, with the curious result that while all the speakers advocated full documentation, and recommended the users of software to read the documentation thoroughly, they all agreed that few if any users did so. A member of the audience expressed the view that the whole exercise was useless, because although every programmer was willing to look at someone else's software, in the end he preferred to write his own. Nobody produced an answer to this comment on the spur of the moment, and on this rather inconclusive note, the Symposium ended.

Discussion. Nearly all the advice offered was in line with current practice in the Synoptic Climatology Branch of the Meteorological Office, and at the end of the Symposium I was left with the comfortable feeling of M. Jourdain who consulted the professors, and found that he had been talking prose all his life. Many other meteorological programmers would probably have reached the conclusion that no great changes are called for in their present methods, but suggestions were made under three headings which, if properly exploited, could enable meteorologists to do more useful work in less time, or at lower cost. These are:

- (a) Suggestions for a selective library of algorithms on specific topics, as outlined by the Numerical Algorithms Group.
- (b) Advice for improving the technique of developing effective computer programs, from Dr Larmouth and Mr Ritchie.
- (c) Advice on the choice of software systems (which are specialized computer languages) or packages (which are families of matched subroutines) as discussed by Dr Nelder.

The topics are discussed individually below.

The sum total of published algorithms, including the packages provided by the computer manufacturers, and those published in the *Communications of the Association for Computing Machinery*, *Numerische Mathematik*, the *Journal of Applied Statistics* and elsewhere, not to mention the semi-published algorithms which circulate among scientists, are numerous enough to deter any scientist who looks outside his own field of expertise. If, for example, a meteorologist conceives a technique which at some stage involves finding the complex roots of a polynomial, he can spend a disproportionate amount of time reading about the subject, and finding coding to carry out the operation, without any guarantee that he will arrive at an efficient and stable solution. Conversely, a scientist unfamiliar with the solution of partial-differential equations who attacks the problem without making use of meteorological know-how on the subject runs the risk of wasting a great deal of time on problems which have already been solved. A group which can serve as a central clearing-house for know-how on specific numerical problems, so that any scientist who ventures outside his own field can start from something which corresponds to the best modern practice, could save much duplication of effort, and it seems to me that the work of the Numerical Algorithms Group deserves full co-operation and support.

As regards the development of effective software, the advice of Larmouth¹ seems to me to be almost wholly good, but it is so difficult to obtain hard facts about the time taken by meteorologists to develop software, or the efficiency of the software once it is working, that I can only guess how far the meteorological community is in need of such advice. Points on which I have no doubt are that nearly all programs are under-documented, and that while some groups are so strongly staffed that they should be able to maintain very high standards of coding, and as far as I can judge, succeed in doing so, other groups have to spread their programming talent much more thinly and may have difficulty in improving their software once it fulfils its main purpose. The main limitation of Dr Larmouth's advice is that some of it seems rather high-powered for a good many programmers who, from experience within the Office, are quite

capable of doing useful work, and I suspect that the majority of readers, especially those using an IBM computer, would benefit by reading in addition Kreitzberg and Schneidermann,² and Day.³ However, now that meteorologists have been living with computers for 15–20 years, there must be a good many who have worthwhile thoughts on the techniques which make for an inspiring, or at least a tolerable existence, and it is about time that more of these thoughts appeared on paper.

As regards computer systems and packages, these try to go further than the other proposals towards solving the user's software problems, and deserve to be taken seriously. However, it is clear that much more is needed in the way of free discussion and the exchange of information, before it can be seen whether any system developed outside the meteorological world can be a cost-effective solution to any meteorological need. The need for more information is shown by the facts that Schucany, Minton and Shannon⁴ list no fewer than 37 systems and packages concerned with statistics alone, while the meteorological workload, currently running at about 4500 jobs per week, comes from about 20 groups of programmers, most of whom are far too busy solving their own problems to have much time for the cross-fertilization of ideas. The systems that I have examined, however, seem to suffer from at least three disadvantages. A great deal of effort is spent on providing facilities which are unnecessary to meteorologists, either because they are available already, or because there is no demand for them, so that the full cost of the system has to be balanced against the potential value of a small part of the coding; there are features in the working environment of a meteorological office, involving the real-time handling of vast numbers of data as a prelude to elaborate scientific computations, which cast doubt on the applicability of any coding developed in an institution not subject to the same constraints; and in the systems which are good technically, the descriptive documentation seems to be aimed at readers more highly qualified than the staff who would in practice have to use them. Unless these objections can be overcome, I do not rate the prospects of acceptance of any system highly compared with those of the products of the Numerical Algorithms Group.

A further comment, which applies also to software produced within the meteorological world, is that there is no point in a software designer producing a program which is, in his opinion, the perfect solution to a computing problem if he fails to persuade the prospective customer to use it. The psychology of computer users is an intensely interesting subject, the importance of which became evident during the Symposium, and I think that the essential point is that once a programmer has enjoyed the freedom to solve his own problems in his own way (which comes from real fluency in a computer language) he will never willingly surrender that freedom, so that software which in effect restricts his freedom of choice will be rejected out of hand. However, if the software designer is willing to accept the principle that the customer is always right, and simply to provide what is asked for, the prospects of fruitful co-operation are much brighter. This agrees with my own experience, in the Meteorological Office, but the amusing article by Cutbill and Jones⁵ suggests that the same tensions also occur elsewhere. However, my purpose at this stage is not to suggest solutions, but simply to argue that the value of computer systems, or more generally of techniques for getting useful work out of a computer, is not

something which can be measured wholly by abstract standards, but must be judged against the needs of real people in a real working environment, and that what is needed at present is more information about working situations, and about the needs which are felt to be pressing by the people in these situations, to provide the systems designers with the material to work on. I suggest that meteorologists in different fields should try to publicize their own software problems, and the working environments which give rise to these problems, by offering contributions either to this journal, or to one more specifically concerned with software.

REFERENCES

1. LARMOUTH, J.; Serious FORTRAN. *Software, Practice and Experience*, London, 3, 1973, pp. 87-107 and 197-225.
2. KREITZBERG, C. B. and SCHNEIDERMAN, B.; The elements of FORTRAN style: techniques for effective programming. New York, Harcourt, Brace, Jovanovich Inc., 1972.
3. DAY, A. G.; FORTRAN techniques with special reference to non-numerical applications. London, Cambridge University Press, 1972.
4. SCHUGANY, W. R., MINTON, P. D. and SHANNON, B. S.; A survey of statistical packages. *Computing Surveys*, London, 4, 1972, No. 2, pp. 65-79.
5. CUTBILL, J. L. and JONES, KAREN S.; The needs of the pseudo-pro. *Software, Practice and Experience*, London, 3, 1973, pp. 83-86.

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MESOSCALE STRUCTURE OF JET STREAMS AND ASSOCIATED CLEAR-AIR TURBULENCE

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Summary. Large-amplitude clear-air 'billow' echoes due to clear-air turbulence as observed by the Defford high-power radar are displayed on time-height sections, corresponding to the passage of five upper-tropospheric jet streams. The occurrence of the billows is discussed in relation to the time-height sections of wind speed, magnitude of the vector vertical wind shear and vertical gradient of potential temperature derived from sequential radiosonde ascents made during the passage of the jet streams.

The Roach Index, Φ , is illustrated for three of the case studies. Large-amplitude billows were detected in regions where $\Phi > 10^{-4} \text{ s}^{-1}$.

Introduction. Theoretical considerations and observations in the laboratory, ocean and free atmosphere suggest that most clear-air turbulence (CAT) is in the form of unstable waves due to Kelvin-Helmholtz instability (KHI) which develops within stably stratified, quasi-horizontal flows in the presence of strong shear. It is well known, too, that CAT is associated with distinctive features in the upper-air flow (Roach¹) and, in particular, with regions of strong vertical wind shear in the vicinity of jet streams. An analysis of a number of case studies by Browning² has shown the relationship between the occurrence of KHI detected by high-power radar and mesoscale atmospheric structure in its immediate vicinity. There is, however, a shortage of data concerning the nature of mesoscale regions of preferred KHI development

* Now at Headquarters Strike Command and St Mawgan respectively.

in relation to synoptic-scale features such as jet streams. This paper is seen as an extension to the work of Browning² and its purpose is not only to seek to clarify the relationship of large-amplitude Kelvin-Helmholtz (KH) billows to mesoscale features of atmospheric structure (e.g. vector vertical wind shear and vertical gradient of potential temperature) but also to investigate the characteristics and distribution of the mesoscale features in relation to the synoptic-scale pattern.

Terms such as 'strong shear' have a precise meaning throughout the paper and these definitions will now be introduced formally:

weak shear	$ \Delta V/\Delta z $ less than 5 m/s per 400 m,
strong shear	$ \Delta V/\Delta z $ between 5 and 10 m/s per 400 m,
very strong shear	$ \Delta V/\Delta z $ in excess of 10 m/s per 400 m,
weak stability	$\Delta\theta/\Delta z$ between 2 and 6 degC per 400 m,
strong stability*	$\Delta\theta/\Delta z$ between 6 and 10 degC per 400 m,
very strong stability	$\Delta\theta/\Delta z$ in excess of 10 degC per 400 m,
low Richardson number	Ri less than 0.5.

Data acquisition, analysis and presentation. The case studies to be discussed were obtained during the passage of jet streams overhead or nearby. During operational periods, each generally of at least 8 hours' duration, data were obtained by two methods; observations of echoes from clear air by the high-power radar at the Royal Radar Establishment, Defford and soundings from radiosondes tracked by precision radar.

The Defford 107-mm wavelength radar has been described by Watkins.³ CAT gives rise to turbulent flow on a range of scales down to those smaller than half the radar wavelength and the resulting refractive-index irregularities are detected by the radar. Aircraft penetration of these clear-air echo layers and billows (Glover *et alii*,⁴ Glover and Duquette,⁵ Browning *et alii*⁶ and Mather and Hardy⁷) have confirmed that they are indeed associated with CAT.

In the present study the high-power aerial scanned continuously in the vertical plane from 0° to 90°, into the direction of the upper-tropospheric winds, at the rate of about 1 scan every 2½ minutes. Resulting echoes were displayed and photographed on a conventional Range-Height Indicator (RHI) display. The limit of resolution of the radar in the vertical is typically 100 to 200 m (pulse length 187 m, half-power beam width 0.33° in the vertical and horizontal) and it was only possible to resolve clearly the structure of billows with amplitudes in excess of 200 m. Horizontal trains of billows with much smaller amplitudes were detected as almost featureless layer echoes. Although the resolution and sensitivity of the radar limits the range and height to which very slight CAT due to small-amplitude KHI may be detected, it can reasonably be expected that the radar will detect all large-amplitude billows (i.e., crest-to-trough amplitude in excess of 400 m) associated with at least slight turbulence within a range of about 15 km and lying below a maximum height of 12 km. Hourly radiosonde ascents from the Royal Radar Establishment's Pershore site, 8 km north-east of Defford, permitted good resolution of mesoscale atmospheric structures. Temperature data were evaluated with a maximum resolution obtainable at height intervals of about 100 m, giving an

* The corresponding $\Delta\theta$ over 400 m for an isothermal lapse is as follows: 4 degC at a height of 4 km; 6 degC at a height of 8 km; 8 degC at a height of 12 km.

r.m.s. error in $\Delta\theta$ of about 0.2 degC. The use of data at 20-second intervals permitted ΔV to be evaluated over height intervals of 400 m with an r.m.s. error usually about 0.5 m/s.

Since a long-term aim of CAT studies is to devise improved techniques whereby routine synoptic-scale radiosonde data supply the input for predicting regions of CAT, the vertical resolution of shear, etc., has been taken over deep layers ($\Delta z = 400$ m). This depth still provides a vertical resolution comparable with the depth of the deeper dynamically unstable layers which are the subject of this study. Of course, the Richardson number (Ri) may often be critical over shallow layers while its bulk-value over 400 m is above critical. Correlations of CAT occurrence with estimates of Ri based on routine radiosonde observations will therefore be too low except perhaps in the case of KHI which occurs over deep layers.

Results. Figures 1(a-e) illustrate the locations of the observations, AB, made in the vicinity of the jet core on the case-study days, displaced relative to the jet according to the system velocity.

The families of time-height cross-sections, forming the basis of the data presented in this paper, are illustrated in Figures 2-6. Cross-sections are as follows: (a) horizontal wind speed, V , (b) magnitude of the vector vertical wind shear, $|\Delta V/\Delta z|$, and (c) vertical gradient of potential temperature $\Delta\theta/\Delta z$. Figures 7 (a-c) show the Roach Index, Φ . This index (Roach⁸) is intended to be a measure of the probability of occurrence of CAT, and has been computed using data from radiosonde ascents. Occurrences of large-amplitude billows with crest-to-trough amplitude in excess of 400 m are represented by crosses in each set of sections. Virtually continuous radar surveillance was maintained so that the absence of a cross can properly be interpreted as indicating the absence of significant large-amplitude billow events in the vicinity of Defford.

(a) 6 February 1970 (10 GMT to 1930 GMT). At low levels a region of high pressure over the southern half of the British Isles receded towards the south-east during the period and south-westerly winds became established. The warm front which preceded a narrow warm sector eventually passed through the Defford area at about midnight. A strong northerly upper flow was maintained over the area throughout the period and was advancing across the British Isles from about 300° at 13 m/s. Observations were made within a region of relatively straight flow between trough and ridge during the passage of the jet from the cold to the warm side (Figure 1 (a)). The section passed into the jet core at 14 GMT and out of it at 1630 GMT. Time-height sections of V , $\Delta V/\Delta z$ and $\Delta\theta/\Delta z$ are displayed in Figures 2 (a), (b) and (c) respectively. An intense KH billow (crest-to-trough amplitude 400 m) occurred at 1243 GMT within the frontal zone in a region of very strong shear, strong stability and low Ri . Figure 7 (a) presents the distribution of the Roach Index, Φ . The single large-amplitude billow event was associated with a value $\Phi = 15$ in a region of strong Φ gradient.

(b) 18-19 February 1971 (17 GMT to 05 GMT). Throughout the period a trough lay parallel to and just off the east coast, its southern end curving eastwards towards the centre of a filling depression over the Danish-German border. At low levels west-north-westerly winds over most of England and Wales preceded a warm frontal system approaching from the Atlantic. The main

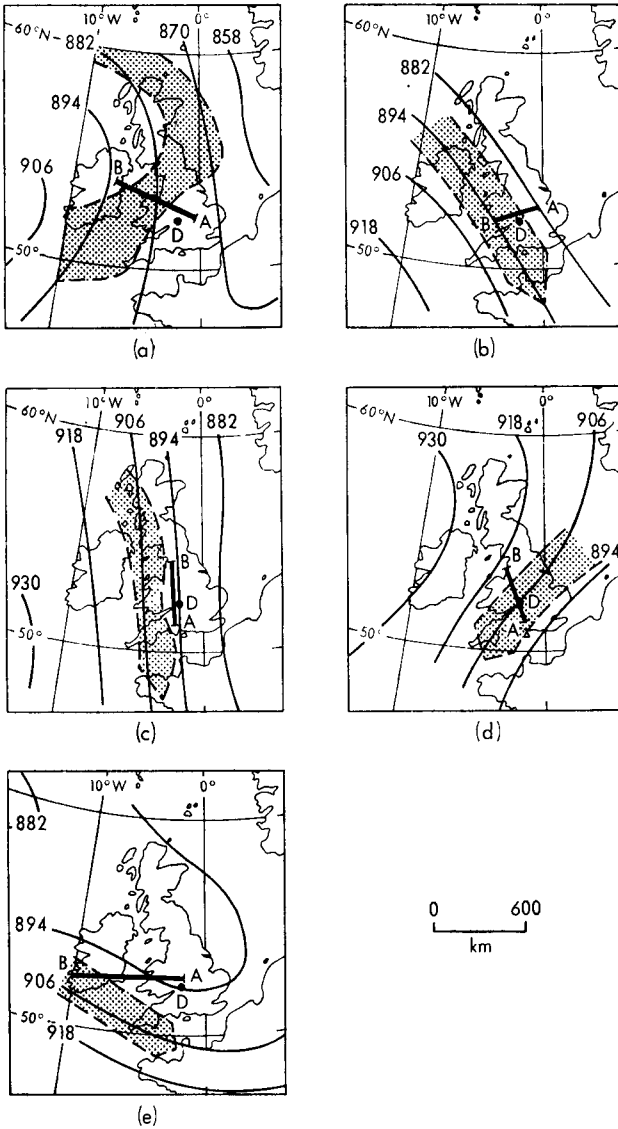


FIGURE 1—APPROXIMATE LOCATIONS OF CROSS-SECTIONS (AB) PRESENTED IN FIGURES 2–7 RELATIVE TO THE JET CORE

- (a) 12 GMT on 6 Feb. 1970, system velocity $12\frac{1}{2}$ m/s at 300° ,
- (b) 00 GMT on 19 Feb. 1971, system velocity 6 m/s at 250° ,
- (c) 12 GMT on 23 Nov. 1971, system velocity 12 m/s at 355° ,
- (d) 12 GMT on 24 Nov. 1971, system velocity 10 m/s at 340° ,
- (e) 12 GMT on 10 May 1972, system velocity $17\frac{1}{2}$ m/s at 270° .

The stippled arrow represents the core of maximum winds. The limits of the jet core are defined as being where the wind speed falls 5 m/s below core maximum. Heights of the 300-mb contours are in decametres. A denotes location of the earliest radiosonde at launch, B that of the last of the period; D shows location of Defford/Pershore.

centre of this system was in mid Atlantic at about 55°N and south-east of the centre was a very wide warm sector. The main warm front lay just west of Cork and the Scillies at 06 GMT on 19 February. On earlier charts there had been some evidence of a weak preliminary warm front with a similar orientation (north-north-west to south-south-east) lying about 600 km ahead of the main warm front. The stable regions associated with both warm fronts show up well in the $\Delta\theta/\Delta z$ analysis in Figure 3 (c), the weak front featuring as the roughly horizontal stable layer at 4 km. The jet core advanced east-north-eastwards to be overhead at Defford at 2130 GMT (Figure 1 (b)). Maximum wind speeds within the core were 70 m/s and both the billow events observed, (crest-to-trough amplitude 500 m) occurred within very strong shear regions (Figure 3 (b)), one just above the jet core and the other just below. One patch of billows occurring at 0115 GMT at a height of 8.3 km and with amplitude of 800 m was associated with a thick cirrus cloud layer and hence is not counted as true CAT.

(c) 23 November 1971 (09 GMT to 18 GMT). A warm front approached western Scotland from the Atlantic and by 18 GMT lay north-south at about 15°W. A northerly jet covered the British Isles. The section (Figure 1 (c)), (assuming a mean system movement of 12 m/s at 355°), was in an area of straight contours between ridge and trough. The west-to-east component of jet movement in the latitude of Defford was minimal, very slight fluctuations in its position resulting in observations being commenced just on the cold side and moving into the core region itself at about 10 GMT, reverting back to just on the cold side by 17 GMT. At no stage was the section more than 100 km from the core centre. Zones of strong shear and stability (Figures 4 (b), (c)) descended from 7 km to 6 km in height during the period and are almost certainly associated with the slowly approaching warm front. Large-amplitude KH billows were observed for several hours after 09 GMT. They occurred in strong and persistent regions of shear and stability below the main frontal zone. The 800-m crest-to-trough amplitude of these billows was the greatest observed throughout the periods of the case studies. Their longevity may be due to the orientation of the section with respect to the jet core with the result that the observations were obtained in the same relative location over a long period. Since the billows were advecting southwards at the speed of the winds at their altitude, they may have comprised a train some 100 km in length. However, the

Notes on Figures 2-6, (a), (b) and (c)

These figures show a series of time-height cross-sections of the atmosphere derived from data from the Pershore sequential radiosonde ascents. Two distance scales appear above each figure. The upper one indicates the equivalent distance along the section assuming the system velocity in the corresponding Figure 1. The other scale gives a measure of the distances of the section from the jet-core axis (+ on the cold side, - on the warm) with a probable error of ± 50 km. Arrows at the foot of each set of figures show times of radiosonde data. Crosses represent position, duration and maximum amplitude of KH billows with crest-to-trough amplitudes in excess of 400 metres. In each set of figures the sections are as follows:

- (a) Horizontal wind speed, V , averaged over 400 m. Solid lines are isotachs at 10-m/s intervals.
- (b) Magnitude of vector vertical wind shear $\Delta V/\Delta z$ over 400 m. Hatched and close-hatched shading correspond to strong and very strongly sheared layers ($\Delta V/\Delta z$ of 5-10 and > 10 m/s per 400 m respectively). J indicates the core of maximum winds.
- (c) Vertical gradient of potential temperature $\Delta\theta/\Delta z$ over 400 m height. Hatched, close-hatched and solid shading correspond to weak, strong and very strong stability ($\Delta\theta/\Delta z$ of 2-6, 6-10 and > 10 degC per 400 m respectively). J indicates the core of maximum winds. The dotted line represents the conventional troposphere.

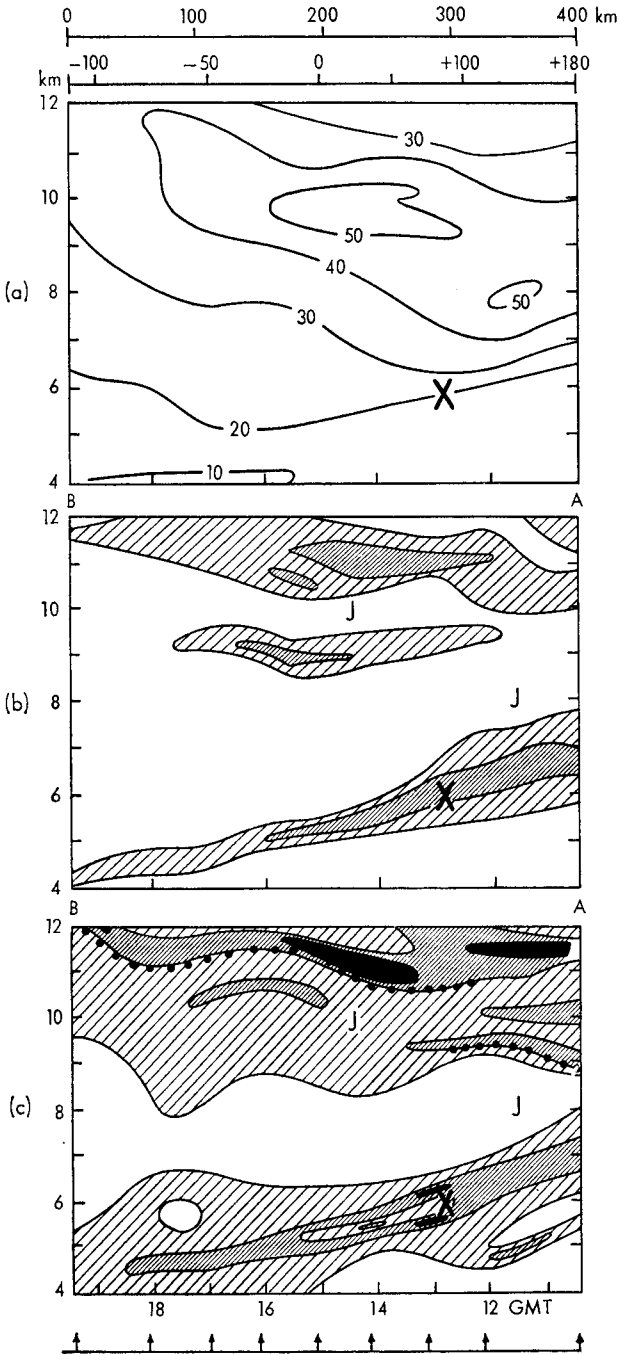


FIGURE 2—TIME-HEIGHT CROSS-SECTION, 12 GMT ON 6 FEBRUARY 1970
See notes on page 317.

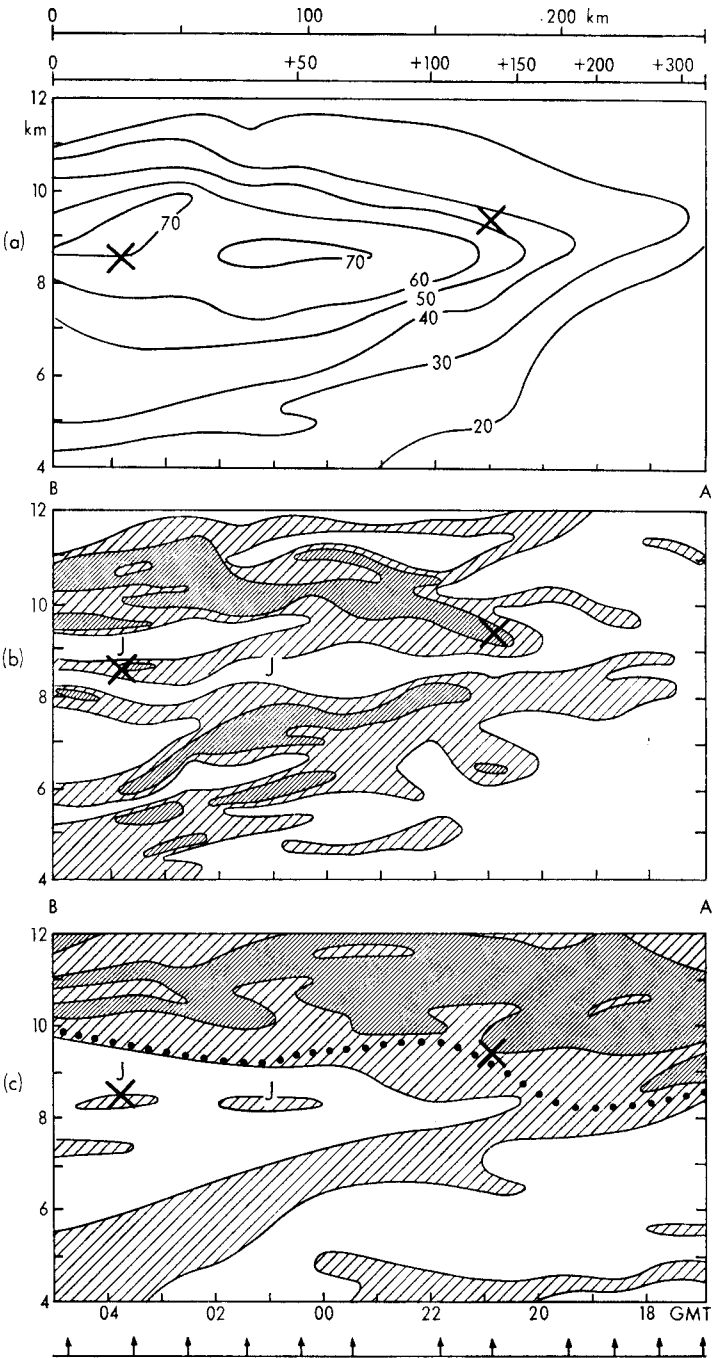


FIGURE 3—TIME-HEIGHT CROSS-SECTION, 00 GMT ON 19 FEBRUARY 1971
See notes on page 317.

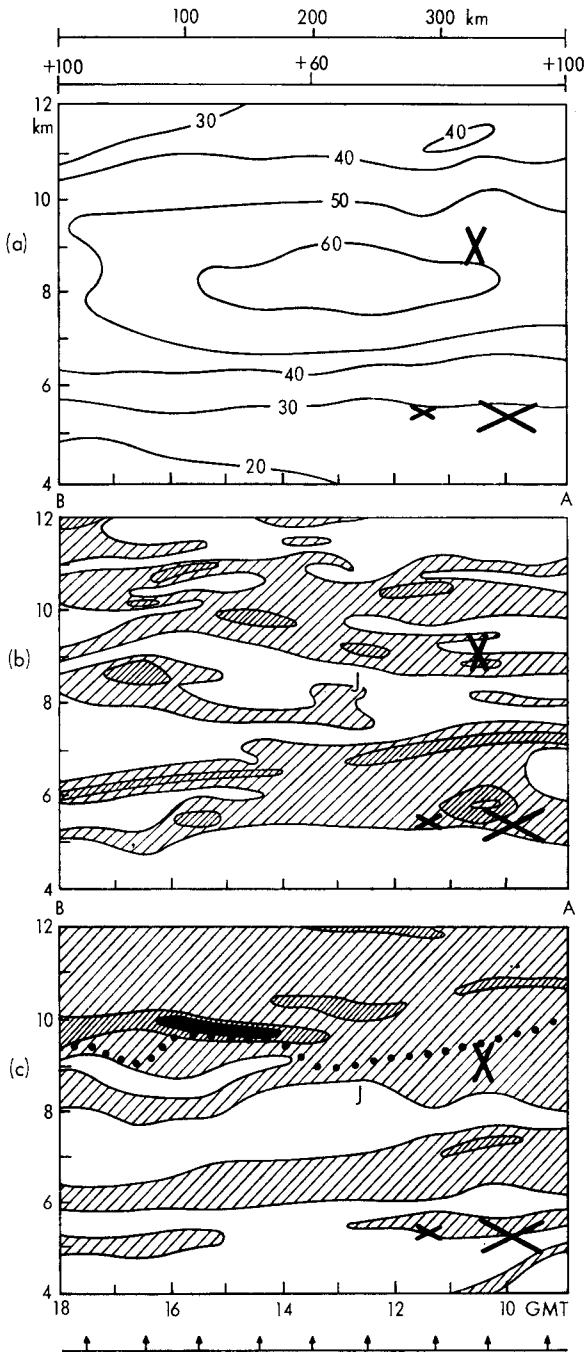


FIGURE 4—TIME-HEIGHT CROSS-SECTION, 12 GMT ON 23 NOVEMBER 1971
See notes on page 317.

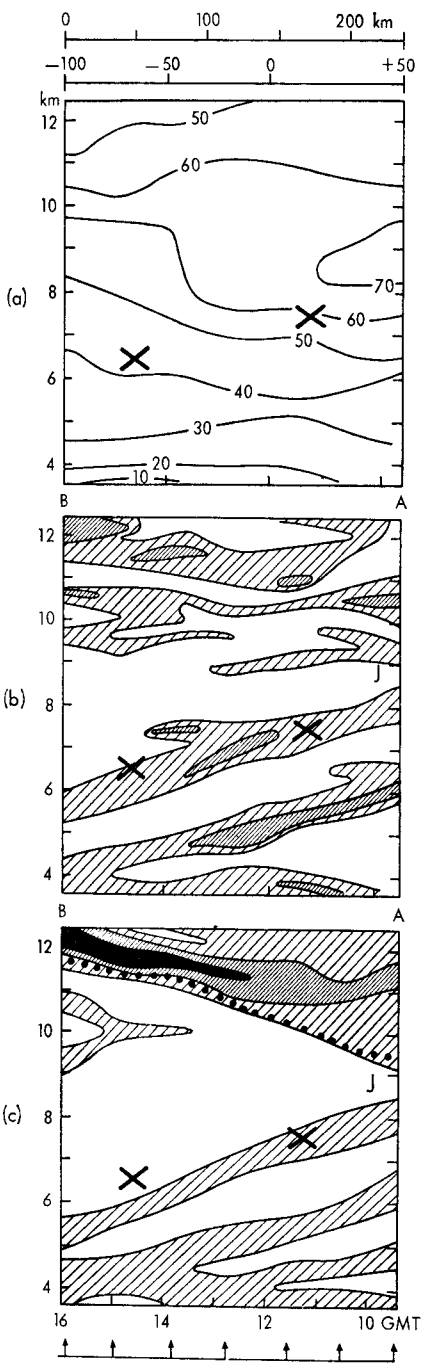


FIGURE 5—TIME-HEIGHT CROSS-SECTION, 12 GMT ON 24 NOVEMBER 1971
See notes on page 317.

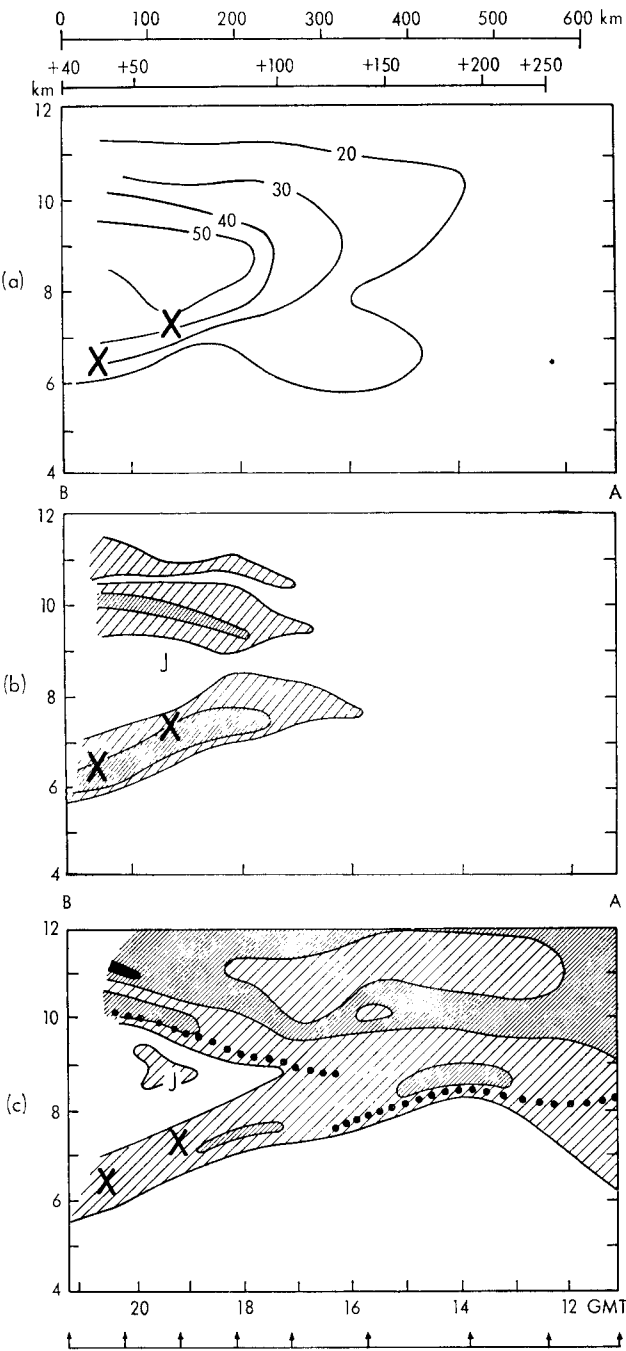


FIGURE 6—TIME-HEIGHT CROSS-SECTION, 12 GMT ON 10 MAY 1972
See notes on page 317.

possibility cannot be overlooked that the billows were initiated just in the vicinity of Defford by minor topographic influences.

(d) 24 November 1971 (0930 GMT to 16 GMT). A warm front oriented north-east to south-west moved rapidly south-eastwards into Scotland. This front was associated with a filling, but deep, depression which moved south-eastwards from Jan Mayen during the period. Behind the front was a broad north-westerly warm sector. A north-easterly jet associated with the front moved south-eastwards across the region (system velocity 10 m/s at 340°). Contours over the Defford area were slightly cyclonically curved. The section was made mainly within the core (Figure 1 (d)) extending into the warm side after 15 GMT and being about 100 km from the jet axis at the end of the period. Winds in the core exceeded 70 m/s. Two tongues of high shear associated with the approaching fronts descended from 6 km at 0930 GMT to $4\frac{1}{2}$ km at 1330 GMT (Figure 5 (b)). The corresponding well-marked stable zones are seen in Figure 5 (c).

Two KHI 'events' were recorded, with amplitudes in excess of 400 m. The two large-amplitude billows were detected by the radar at 1110 GMT at a height of 8 km and occurred within the upper frontal zone.

The Roach Index, Φ (Figure 7 (b)), attained a maximum over Defford before 12 GMT and the two billow events occurred in a region of maximum Φ which lowered and weakened with time in association with the passage of the twin frontal zones. In the next six hours the maximum in Φ at 300 mb was computed to move south-eastwards over northern France and decline, the movement of a corresponding area of CAT being corroborated by turbulence reports from pilots (Brown⁹).

(e) 10 May 1972 (11 GMT to 21 GMT). A cold front lying south-south-west from a small depression in the Channel progressed eastwards during the period. A further frontal system was approaching western Ireland towards the end of the period by which time the general north-westerly wind at low level over much of England and Wales was giving way to a weak ridge moving slowly in from the west. A sharply diffluent upper trough over the north-eastern half of the British Isles pushed south-eastwards into Europe while a north-westerly jet associated with the approaching Atlantic frontal system extended steadily across the south-western half of England. The contour pattern showed slight anticyclonic curvature at the start of the period but became straighter subsequently. The system moved from 270° at $17\frac{1}{2}$ m/s. An initial rise of the stable layer at about 8 km on the $\Delta\theta/\Delta z$ section (Figure 6 (c)) is probably associated with the receding cold front. Thereafter the lowering ahead of the warm front approaching Ireland is sharply defined. The section was made from the cold side of the jet, entering the core at 1740 GMT (Figure 1 (e)). Until about 16 GMT the wind speed was less than 30 m/s. Figure 6 (b) shows that, as the jet core approached, the horizontal and vertical velocity gradients tightened considerably; at $8\frac{1}{2}$ km the wind speed increased by 20 m/s in the hour 17 to 18 GMT. The implied cyclonic shear during this period was an order of magnitude greater than the Coriolis parameter. Billow echoes were absent until at least 16 GMT (when the radar surveillance was interrupted for servicing) and probably until 1810 GMT since only one minor layer echo (at a height of $4\frac{1}{2}$ km) was detected when radar observations were resumed at this time. This assumption is supported by data from the 1708 GMT radiosonde which did not show any

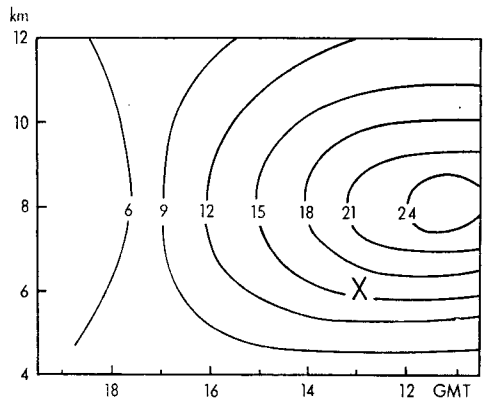


FIGURE 7 (a)—THE ROACH INDEX, Φ , APPLIED TO FIGURE 2
Units are expressed in 10^{-8} s^{-1} .

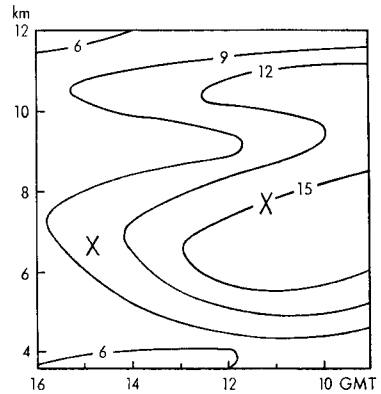


FIGURE 7 (b)—THE ROACH INDEX, Φ , APPLIED TO FIGURE 5
Units are expressed in 10^{-8} s^{-1} .

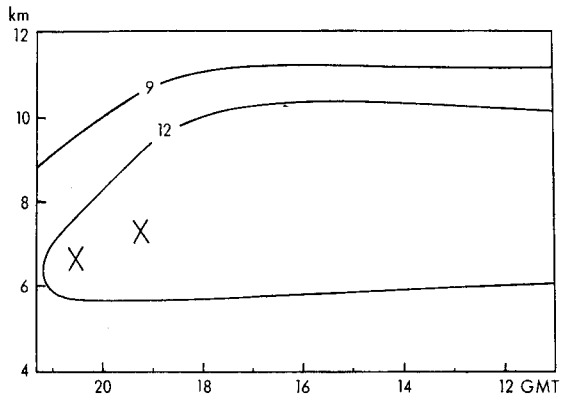


FIGURE 7 (c)—THE ROACH INDEX, Φ , APPLIED TO FIGURE 6
Units are expressed in 10^{-8} s^{-1} .

regions where $Ri < 0.5$. A well-marked region of CAT developed within the frontal zone soon after 18 GMT. Over a $2\frac{1}{2}$ -hour period the layer lowered, following the slope of the frontal zone, and two occurrences of large-amplitude KH billows were observed.* Both billow trains occurred within a region where the Roach Index was in excess of $12 \times (10^{-5} \text{ s}^{-1})$ (Figure 7 (c)).

Discussion. During the 40 hours of radar observations comprising the case-studies large-amplitude billow echoes (crest-to-trough amplitude in excess of 400 m) were detected for about 5 hours, i.e., as much as 12 per cent of observing time. It is important to remember, however, that periods of observation were deliberately chosen to be during periods considered favourable for the development of CAT.

Table I presents the number distribution of the large-amplitude billows as a function of shear, stability and Richardson number.

All 10 large-amplitude billows occurred in regions of low Ri and strong shear; indeed 7 of the billows developed under the conditions of low Ri and very strong shear (as defined formally in the Introduction). It would appear, then, that the 400-m vertical resolution with 1-hour time spacing of the sequential radiosonde data is adequate to resolve the mesoscale features responsible for all large-amplitude KH billows.

The detailed time-height sections derived for each of the case studies, demonstrate the existence of mesoscale regions of relatively strong shear and stability embedded within the synoptic scale zones (as described also by Barbé¹¹) which may be responsible for the patchy occurrence of CAT (smaller-scale regions may be generated by previous occurrences of CAT; Browning¹²). Inspection of the time-height sections reveals, however, that suitable combinations of very strong shear and low Ri do occur quite often without billows being observed in the vicinity of Defford. It should be remembered that the CAT observations were obtained from a single site covering a range of typically 15 km. Billows may have occurred within the layers of suitable ΔV and Ri when just out of range of the Defford radar.

A brief statistical interpretation of the data is presented in the form of histograms of the frequency of occurrence of certain mesoscale features derived from data from the 46 radiosonde ascents made during the five case studies. Figure 8 depicts the depth overhead of regions of strong stability. It shows that almost 50 per cent of these layers had a vertical half-width of less than 1 km while about 30 per cent of the layers had a vertical half-width of more than 2 km; these regions occurred mainly near the tropopause. The corresponding histogram for the depth overhead of very strong shear regions is portrayed in Figure 9. The vertical half-width of 66 per cent of these layers was less than 1 km, the modal value being 400 to 600 metres.

* During these periods of KH billows, information from the high-power radar display permitted the instrumented Canberra of the Meteorological Research Flight to be directed into the billows. Simultaneous records of Doppler radar measurements of the billow pattern and aircraft response were obtained, the aircraft reporting moderate to severe turbulence as it encountered the well-defined billow train at 1910 GMT. These and other results of a joint CAT Study Programme run by the Meteorological Office Special Investigations Branch, the Meteorological Research Unit, Malvern and the Meteorological Research Flight, Farnborough have been evaluated (see for example Browning, Bryant, Starr and Axford¹⁰).

TABLE 1—THE OCCURRENCE OF LARGE-AMPLITUDE KH BILLOWS AS A FUNCTION OF SHEAR, STABILITY AND RICHARDSON NUMBER

Event	Date	Height <i>km</i>	Duration GMT	Minimum crest/trough amplitude <i>m</i>	Δv <i>m s⁻¹(400 m)⁻¹</i>	$\Delta \theta$ <i>deg C(400 m)⁻¹</i>	<i>Ri</i> (For a 400-m deep layer)
(a)	6 February 1970	6.0	1245–1300	15	13.5	6	0.4
(b)	18–19 February 1971	9.5	2040–2116	36	14.8	6.4	0.3
		8.5	0326–0400	34	10.5	2.4	0.2
(c)	23 November 1971	9.0	1025–1040	15	11.5	2.6 to 5.8	0.5
		5.5	1120–1150	30	8.5	2.8	0.4
		5.5	0910–1035	85	14.5	2.5	0.5 to 0.1
(d)	24 November 1971	7.7	1100–1130	30	9.2	3.8	0.2
		6.7	1425–1450	25	6.5	1.2	0.1
(e)	10 May 1972	7.2	1905–1925	20	16.0	5.9	0.3
		6.5	2020–2040	20	14.2	5.1	0.3

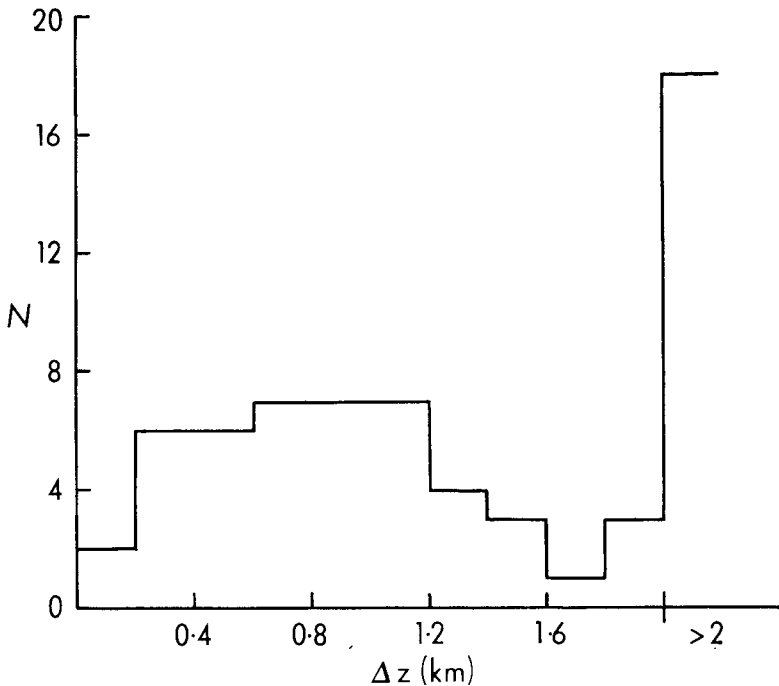


FIGURE 8—NUMBER DISTRIBUTION, N , OF THE VERTICAL HALF-WIDTH, Δz , OF LAYERS OF STRONG POTENTIAL TEMPERATURE GRADIENT (IN EXCESS OF 6 degC PER 400 m)

Data are derived from a total of 46 radiosonde ascents obtained during the five case studies.

The sections of Roach Index are probably subject to larger errors owing to the coarse scale of the input data. They do, however, present the billow events as occurring near maxima of Φ and, in particular in regions of the sections where $\Phi > 10 \times (10^{-5} \text{ s}^{-1})$. This is in line with case studies by Brown⁹ based on aircraft reports of turbulence.

Tables (not presented) were drawn up to display the percentage area of the time-height sections, averaged over the five studies, which were occupied by large-amplitude billows and by regions of very strong shear and low Ri . Estimates were tabulated relative to the position of the jet core. Very strong shear regions occupied about 5 per cent of the area of the time-height sections from 1 km above to 5 km below the jet core and in the range 100 km on the warm side to 200 km on the cold side of the jet core. Large-amplitude billows occupied about 25 per cent of these very strong shear regions between 1 and 3 km below the jet; elsewhere the percentage was much less with an average of about 12 per cent for the section as just defined for the very strong shear regions. The maximum percentage area coverage for regions of low Richardson number occurred within the layer between 1 and 3 km below the axis of the jet and within the column between the axis of the jet and 50 km on the cold side. Large-amplitude billows occupied on average about 4 per cent of these regions of low Ri between 1 km above and 5 km below the jet core and from 100 km on the warm side to 200 km on the cold side of the jet core. A maximum

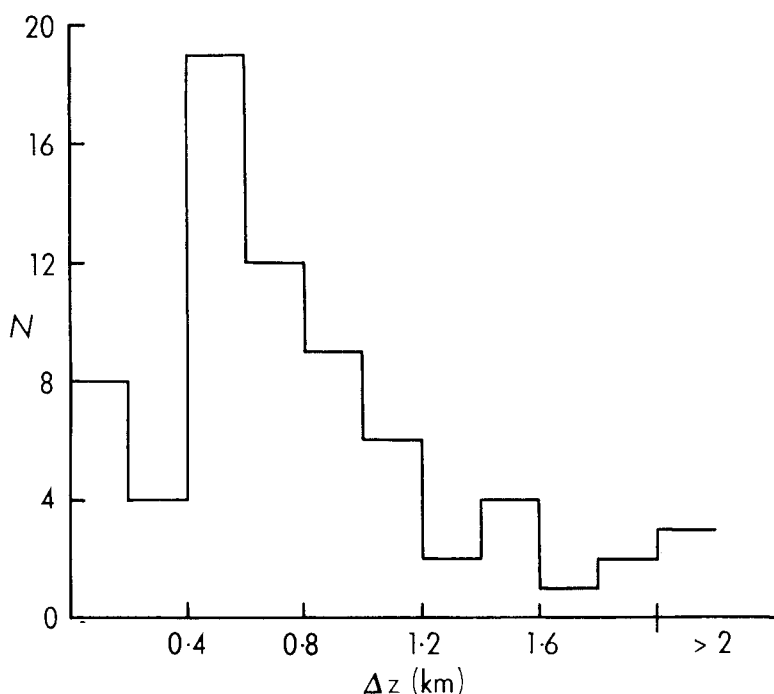


FIGURE 9—NUMBER DISTRIBUTION, N , OF THE VERTICAL HALF-WIDTH, Δz , OF VERY STRONGLY SHEARED LAYERS (MAXIMUM SHEAR IN EXCESS OF 10 m/s PER 400 m)

Data are derived from a total of 46 radiosonde ascents obtained during the five case studies.

of 10 per cent occurred between 1 and 3 km below the jet between the range limits mentioned above. Large-amplitude billows occupied an average of about 10 per cent of areas where conditions of very strong shear and low Ri coexisted.

In conclusion, therefore, it can be said that cross-sections of ΔV and $\Delta \theta$ demonstrate that mesoscale structures responsible for all the observed large-amplitude KH billows can be defined by a sequence of radiosonde ascents. Limitations of fixed-point observations preclude a definite statement as to whether or not CAT occurred within all seemingly suitable mesoscale structures. It seems unlikely, though, that CAT identification based even on hourly radiosonde data such as those presented here, could be framed in other than probability terms.

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The Defford research programme is undertaken under the direction of Dr K. A. Browning.

REFERENCES

1. ROACH, W. T.; Clear air turbulence. Watford, Merrow Publishing Co. Ltd (in press).
2. BROWNING, K. A.; The structure of the atmosphere in the vicinity of large-amplitude Kelvin-Helmholtz billows. *Q J R Met Soc, London*, 97, 1971, pp. 283-299.
3. WATKINS, C. D.; High power radar for meteorological studies in clear air. *Proc Inst Elect Engrs, London*, 118, 1971, pp. 519-528.
4. GLOVER, K. M., BOUCHER, R. J., OTTERSTEN, H. and HARDY, K. R.; Simultaneous radar, aircraft and meteorological investigations of clear air turbulence. *J Appl Met, Lancaster, Pa*, 8, 1969, pp. 634-640.
5. GLOVER, K. M. and DUQUETTE, E. F.; A study of clear air turbulence using sensitive radars. *Proc Fourteenth Radar Met Conf, Tucson, Arizona*, 1970, pp. 89-94.
6. BROWNING, K. A., WATKINS, C. D., STARR, J. R. and MCPHERSON, A.; Simultaneous measurements of clear air turbulence at the tropopause by high-power radar and instrumented aircraft. *Nature, London*, 228, 1970, pp. 1065-1067.
7. MATHER, G. K. and HARDY, K. R.; Instrumented aircraft measurements in the vicinity of clear air radar structure. *Proc Fourteenth Radar Met Conf, Tucson, Arizona*, 1970, pp. 49-52.
8. ROACH, W. T.; On the influence of synoptic development on the production of high level turbulence. *Q J R Met Soc, London*, 96, 1970, pp. 413-429.
9. BROWN, R.; New indices to locate clear-air turbulence. *Met Mag, London*, 102, 1973, pp. 347-361.
10. BROWNING, K. A., BRYANT, G. W., STARR, J. R. and AXFORD, D. N.; Air motion within Kelvin-Helmholtz billows determined from simultaneous Doppler radar and aircraft measurements. *Q J R Met Soc, London*, 99, 1973, pp. 608-618.
11. BARBÉ, G. D.; Données sur le vent en altitude jusqu'à 30 km et au delà. *J Scient Mèt, Paris*, 10, 1958, pp. 47-62.
12. BROWNING, K. A.; Radar measurements of air motion near fronts. *Weather, London*, 26, 1971, pp. 320-340.

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THE METEOROLOGICAL OFFICE WEATHER OBSERVING SYSTEM (MOWOS) Mk 2

By G. J. DAY, K. J. T. SANDS and B. TONKINSON

Summary. The trial of the Automatic Weather Station (MOWOS Mk 2) is discussed followed by a technical description of the system. Sensors in current use are described and the problems associated with maintenance of remote stations outlined.

Introduction. Between 1965 and 1969, the Meteorological Office conducted experiments with Automatic Weather Stations which featured a range of new sensors and an analogue telemetry and display system. By 1968 it was apparent that both the telemetry system and the meters used in the display console were sources of unacceptable errors, and proposals were made for a new system based on digital stores, telemetry and displays. The new system became known as the Meteorological Office Weather Observing System Mk 2 (MOWOS).

By the end of 1969 approval had been given for the establishment of a pilot network of 8 MOWOS stations in order to assess the overall effectiveness of the new system before proceeding to a larger network. However, it was not until early in 1971 that all the details of the scheme had been settled and approval given for the procurement of 10 sets of equipment. Of the 10 sets 2 were intended for further development work and training.

From the placing of the contract with Hawker Siddeley Dynamics Ltd, work at the contractors and in the Operational Instrumentation Branch was carried out in accordance with 'Programme Evaluation Review Technique' (PERT) diagrams and regular project control meetings were held. It is to the credit of all concerned that the first set of equipment was delivered to the

Experimental Site at Beaufort Park on the day specified at the placing of the contract.

After three months of testing, which led to some minor modifications, the go ahead was given for production and the Contract completed in May 1974. Three sets have so far been installed, at Beaufort Park, South Farnborough and Leuchars, and it is hoped to complete the programme when permission is given for the resumption of works services at the remaining six sites.

When complete, it is expected that the pilot network of 8 MOWOS field stations and associated receiving stations will be similar to that shown in Figure 1. Positions are chosen by the Meteorological Office's Working Group on United Kingdom Observational Networks to be representative of a wide variety of meteorological and operating environments, in order that an assessment can be made of all aspects of the performance of the equipment.

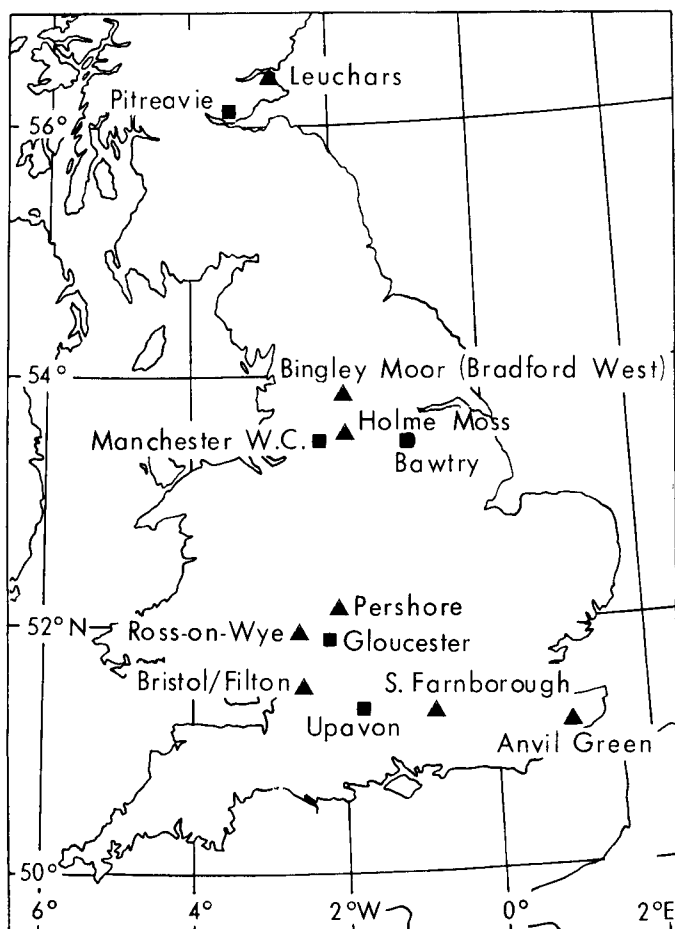


FIGURE 1—PROPOSED PILOT NETWORK OF MOWOS REMOTE AND RECEIVING STATIONS

▲ Remote station ■ Receiving station.

In succeeding sections, the MOWOS system is described and some general comments are made on the role of automatic systems in observational networks.

MOWOS

The remote field station. The remote station accepts the output from the sensors, processes and stores the data and transmits them on demand to the receiving station. Data are transmitted over the public switched telephone network, using the DATEL 400 Service. Stations are located, when possible, to take advantage of Subscriber Trunk Dialling (STD).

Figure 2 shows the layout of the standard MOWOS remote station. The layout conforms to the normal recommendations on exposure of sensors. The data-processing circuits are housed in a weatherproof shelter in the shape of a cube having sides about 2.5 m in length. The walls are well insulated and thermostatically-controlled heaters are provided to maintain the interior of the shelter at a constant temperature of about 20°C. The shelter contains benching and facilities for personnel working on the system during routine or emergency servicing visits. However, experience so far is that servicing in the field is minimal and consideration is being given to redesign of the remote station to facilitate servicing by module replacement.

Output from the meteorological sensors can be of either analogue or digital form. Analogue outputs are converted by interface circuits to a d.c. voltage in the range 0 to 5 volts. The 12 analogue data channels are sampled sequentially at 5-minute intervals and the corresponding voltage converted to 10-bit binary words which are passed through a serial working store into a serial transfer store. If the remote station is interrogated during data transfer, a reply is inhibited until the transfer is complete.

For sensors having a digital output, channels are allocated to specific sensors. Digital information is passed directly from the sensor into the working store and thence into the transfer store at intervals of 5 or 10 minutes depending on the integration time appropriate to the particular sensor.

A group of channels is also used to monitor three precision voltages in the data-processing system, the presence or absence of other critical voltages and the temperature in the shelter.

The remote station contains an accurate quartz crystal clock which provides a precise time for each message and also control pulses for the data-processing system.

Reception of an interrogation signal from the receiving station initiates the following, automatic, sequence of events at the remote station.

- (a) A check is made to determine whether data are being transferred into store.
- (b) Further transfer of data from the working store is inhibited.
- (c) A signal is sent to the receiving station indicating, by a light, that the remote station is ready to transmit data.
- (d) Operation of a 'data' switch at the receiving station initiates the transfer of the contents of the store to a data highway.
- (e) Data are transmitted, preceded by fixed synchronizing words, the station number and the time when the store was last updated. The complete message, or frame, comprises 32 10-bit words.

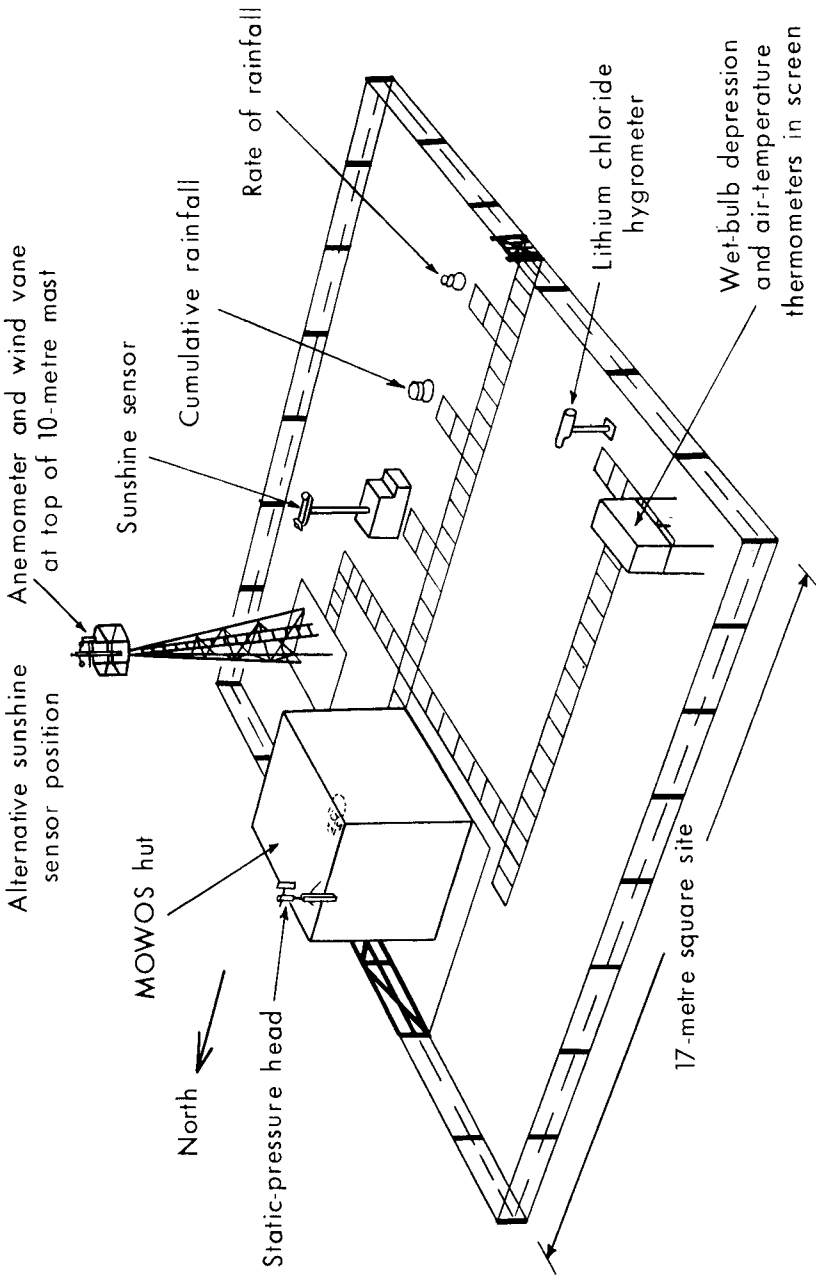


FIGURE 2—MOWOS REMOTE STATION

- (f) Complete frames are repeated, up to eight times and compared word by word at the receiving station. When agreement between corresponding words is achieved, the transmission is terminated. Transmission of eight frames takes 52 seconds but it is rare for more than three frames to be needed to establish parity, that is about 20 seconds from initiating a transmission. Parity checking is described below.

The receiving station. The receiving station is housed in a single-pedestal desk and is illustrated in Figure 3.

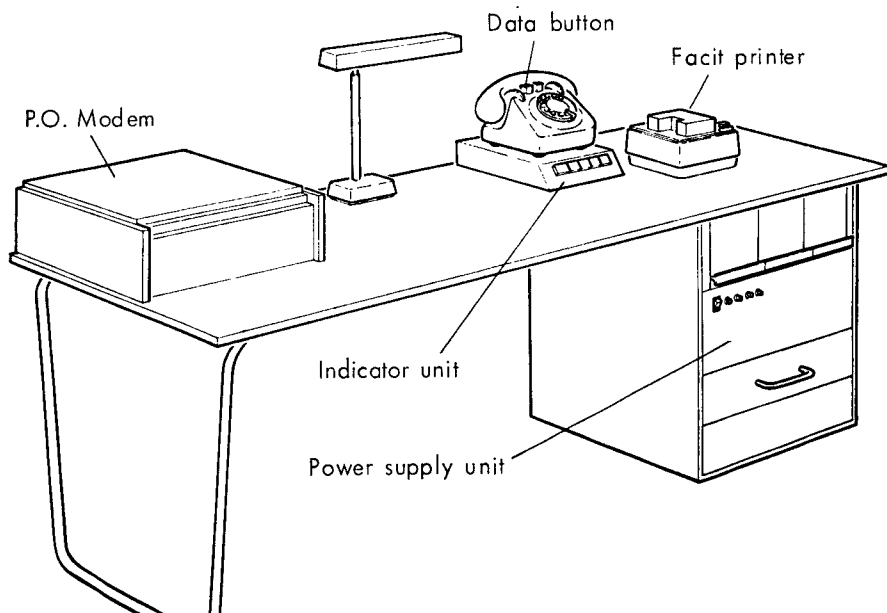


FIGURE 3—MOWOS RECEIVING STATION

Modem is an acronym for modulator and demodulator unit.

When contact with the remote station has been established, two complete frames of data are passed to shift registers and compared bit by bit. Each complete word for which parity is established is passed to a data store in the receiving station and the number of words in the store counted. Successive frames of data are passed into the shift registers, overwriting the oldest frame stored, until 32 words are counted in the data store. Five attempts to establish parity can be made, using 7 complete frames of data; the first frame is always discarded but parity is almost invariably established with the third frame. If parity is not established, an audible and visible alarm is given. Once a complete frame of data is stored, an indicator lights up showing that the telephone handset should be replaced. Replacing the handset disconnects the remote station and initiates the serial transfer of the data from the store. A conversion is now made from the binary code, hitherto used throughout the system, to teletype code and the data are printed by the strip printer. The message is a series of 4-digit words and an elementary code is used which is closely related to engineering units. A typical message is shown in Figure 4.

Station identity (677)	Time hours (1630 GMT)	Time minutes	Sunshine (38 s)	Wind direction (40°)	Wind speed (16 kt)	Blank	Rate of rainfall (5 mm/h)	
0677	0016	0030	0038	= 0040	0016	0000	0050	
Word number	1	2	3	4	5	6	7	8
Cumulative rainfall 64.2 mm	Pressure (985.0 mb)	Dry bulb (11.0°C)	Wet-bulb depression (2.0 degC)	Dew-point (6.8°C)	Blank	Station identity	Time hours	
0321	0425	0410	0020	= 0368	0000	0677	0016	
9	10	11	12	13	14	15	16	
Time minutes	Shelter temperature (20.0°C)	+15 volt precision supply	Positive battery supply (+20 V)	Negative battery supply (-20 V)	Blank	Dewcell inverter supply off/on (on)	Sensor supplies off/on (on)	
0030	0500	307	409	= 409	0000	0000	0000	
17	18	19	20	21	22	23	24	
+15 volts supply off/on (on)	-15 volts supply off/on (on)	Blank	Blank	Blank	Blank			
0000	0000	0000	0000	= 0000	0000	= = =		
25	26	27	28	29	30		End of message	

FIGURE 4—TYPICAL MOWOS MESSAGE FORMAT

The meteorological sensors. MOWOS has been designed to be compatible with standard Meteorological Office sensors, as far as possible, but some of the sensors are currently used only with automatic systems.

The primary sensor suite is as follows:

- (a) Wind speed is measured with a Meteorological Office Mk 4 anemometer. A switch in the anemometer closes every 50 revolutions of the cup rotor and the switch operations in a 10-minute period are counted to give a mean wind speed.
- (b) Wind direction is measured with a Meteorological Office Mk 5 wind vane.¹ The magstrip is energized from a three-phase a.c. power supply, the phase relationship between the magstrip output and its supply being proportional to the wind direction. The phase difference is detected and converted to a d.c. voltage varying from 0 to 5 volts. This voltage is averaged^{2,3} to give a 10-minute mean wind direction which is converted to digital form and stored. The form of averaging used gives most weight to events late in the period.
- (c) Pressure is measured with an aneroid capsule which moves an iron armature within a transformer. This differential transformer is incorporated in a circuit which produces a d.c. voltage in the range 0 to 5 volts and which also compensates for temperature deviations from the standard value obtaining during calibration. A pressure range of 900 to 1050 mb is covered with a resolution of 0.2 mb.
- (d) Temperature, wet- and dry-bulb, is measured with 100-ohm platinum resistance thermometers to BS 1904 Grade I. The dry-bulb thermometer forms one arm of a Kelvin Bridge, the out-of-balance voltage of which is amplified to give a d.c. voltage in the range 0 to 5 volts, representing temperatures from -30 to $+40^{\circ}\text{C}$ with a resolution of 0.1 degC. Wet-bulb depression in the range 0 to 12 degC is similarly obtained by comparing wet- and dry-bulb thermometer resistances in a Kelvin Bridge.
- (e) Dew-point temperature is measured using a lithium chloride hygrometer—often referred to as a 'dew-cell'. This sensor incorporates a platinum resistance thermometer whose resistance is measured with a Kelvin Bridge as in (d) above. The temperature indicated is closely related to the dew-point but small corrections have to be applied, e.g. one for non-linearity and one which is a function of relative humidity. The dew-cell is used to provide dew-points in freezing conditions below 0°C when the wet- and dry-bulb psychrometer is inoperative.
- (f) Cumulative rainfall is measured with a Meteorological Office 750-cm² collector and tipping-bucket switch. Each operation of the switch corresponds to an increment of 0.2 mm of rain and is used to increase the count in the data store. The store is reset when 1023 bucket operations have been counted. In some circumstances tests of the system by servicing personnel may cause the counter to reset before the value 1023 has been reached.
- (g) Rate of rainfall is measured with a drop-counting system. A calibrated orifice attached to a 750-cm² collector forms drops of uniform volume which interrupt a light beam as they fall. An associated circuit causes

the varying output of a photo-electric detector to operate a reed switch, and the number of switch closures in 5 minutes is counted to provide the average rate of rainfall in the period.

- (h) Duration of bright sunshine is measured with a recently developed sensor.⁴ Two matched thermistors are embedded in 5-mm diameter matt-black phosphor-bronze spheres, and each is mounted at the centre of a sealed perspex hemisphere of 10 cm diameter and containing dry air. One thermistor is exposed to the direct sun and the other protected from it by a shade ring. The temperature of each thermistor is a function of the ambient temperature and of the incident radiation. When there is bright sunshine, a difference of temperature is established between the two thermistors which is detected by an associated circuit and used to operate a reed switch. A train of regular pulses is counted when the switch is closed and the number of pulses in 10 minutes is converted to give the number of seconds of bright sunshine during the period.

The design of the shade ring is a compromise. A broad ring reduces the risk of direct radiation reaching the shaded sphere, and also reduces the need for adjustments of the ring as the sun's altitude varies through the year. Too broad a ring, however, causes less sky radiation to reach the shaded sphere than that reaching the exposed one and in a few cases this could lead to false indications of bright sunshine.

The sunshine sensor is intended as a crude indicator of cloudiness, but the correlation between duration of bright sunshine and total cloud amount is not very high.

Care of the system. Care of the MOWOS remote station falls into two parts:

- (a) 'Housekeeping' attention; this is provided by a local caretaker who is engaged to visit the site several times each week. During each visit the site is inspected for damage or obvious malfunctioning of equipment, the grass is cut when necessary and rain-gauges checked for blocking by leaves, insects or bird droppings. Check observations are made of wet and dry-bulb temperature and pressure, and these are telephoned to the Parent Receiving Station. Approximately once a month the screen is washed. Wet-bulb reservoirs are replenished and the wicks changed when appropriate.

It is intended to reduce the number of housekeeping visits in the light of experience, perhaps to about one visit a week. In the growing season, grass cutting may dictate a minimum frequency but regular visits will continue to be required since the sensors are the least reliable part of the system.

- (b) Servicing visits are made by technicians of the Regional Servicing Organization every two months to 'redope' the lithium chloride hygrometer. Every six months, sensors are calibrated with portable apparatus and the electronic system checked by the injection of test signals from a sensor simulator developed in the Meteorological Office. Current evidence is that the mean time between failures (MTBF) for the data-handling system will be excellent, possibly as much as 1 year.

Conclusion. MOWOS is a modern data-acquisition system which has been designed to provide meteorological data with an accuracy comparable with that achieved by the human observer using conventional instrumentation. It has been designed for high reliability even when the data are transmitted over poor-quality telephone circuits.

MOWOS was conceived as a synoptic meteorological system but there is provision for the later addition of a data logger should the data prove to be of an acceptable standard for climatological purposes. The principal use envisaged for the system is the acquisition of data from sites where it is not possible to use human observers, or at times when they are not available. It can therefore be used to fill network gaps in both time and space and, for instance, MOWOS might take over from an observer when a station is unmanned.

The human observer is still essential for such non-instrumental observations as cloud type and present weather. However, if purely instrumental data are acceptable, it has been calculated that MOWOS observations cost only half those of human observers, on a 24-hour basis. MOWOS provides the opportunity to fill the gaps in the present network, and it is possible that a hybrid network will emerge in which man and machine perform complementary rather than overlapping activities.

REFERENCES

1. ELSE, C. V.; The Meteorological Office Mk 5 wind system. *Met Mag, London*, 103, 1974, pp. 130-140.
2. ACHESON, D. T.; An approximation to arithmetic averaging for meteorological variables. *J Appl Met, Lancaster, Pa*, 7, 1968, pp. 548-553.
3. PAINTING, D. J.; An analogue direction-averaging circuit for the Mk 5 wind system (unpublished, copy available in the Meteorological Office, Operational Instrumentation Branch, Beaufort Park, Bracknell).
4. KIRKPATRICK, W. A.; A sunshine sensor for automatic weather stations. Geneva, World Meteorological Organization, Commission for Instruments and Methods of Observation, 6th Session, Helsinki, August 1973, CIMO VI, Scientific Discussions, 1973, pp. 22-27.

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CLIMATE AND FOOD PRODUCTION

One outstanding feature of the *weather* in most parts of the world is its variability; tomorrow it may be much warmer than today, next winter may be much wetter than last winter. But when we speak of the *climate*, which is usually considered as the average weather at a given place over a period of 10 years or more, we tend to think of something which is fairly stable. In fact, however, the climate does fluctuate from one decade to the next and there are longer-term trends in climate from one century to the next. For example, there is some evidence that the average temperature of the northern hemisphere rose by about 0.6 degC between 1900 and 1940, since when it has fallen again by about 0.3 degC. These changes may seem very small but they can be very important for agricultural production, especially in marginal areas where the changes may in any case be somewhat larger than the average change for the whole hemisphere. At the present time when the world has difficulty in

producing enough food for its growing population, and when the grain reserves are already almost exhausted, it is obvious that Man is becoming more sensitive to fluctuations in weather and climate.

The July number of the *WMO Bulletin* contains two articles which are relevant to the above concerns. In 'World Weather Watch and wheat', a Canadian agricultural meteorologist, George W. Robertson, describes how predictions of the yield of wheat in any year can be made more accurately with the help of weather data. Such predictions are of course of great value for agricultural and economic planning. In 'Fluctuations of climate—monitoring and modelling', Professor John Kutzbach of the University of Wisconsin reviews the changes and the steps which must be taken to improve our understanding of climate.

Leading scientists from about 15 countries met in Stockholm from 29 July to 9 August this year to discuss our present knowledge of the theory of climate. This conference was convened by the World Meteorological Organization and the International Council of Scientific Unions within the framework of the Global Atmospheric Research Programme and with support from the United Nations Environment Programme. Special attention was given to the development of improved mathematical models of the atmosphere which, with the aid of powerful computers, can be used to assess the long-term response of the atmosphere-ocean-land system to changes in any of the basic factors which determine climate. Reports were presented on experiments made with such models to compute, for example, the effect of a change in solar radiation, an increase in the carbon dioxide in the atmosphere and an increase in atmospheric pollution. Further work on atmospheric models should help to improve our understanding of the mechanisms which are responsible for climatic change, both natural and man-made.

Most scientists would agree that, in view of the growing economic and social impact of year-to-year variations in weather and of any long-term trends in climate, a major international scientific effort is called for in order to determine whether such variations and trends can be predicted. WMO is now giving increased attention to these questions.

WMO PRESS RELEASE

NOTES AND NEWS

Retirement of Mr L. Sugden

On 3 November 1974 Mr Leo Sugden retired from the Meteorological Office, where for the past four years he held the post of Assistant Director, Public Services.

Mr Sugden gave up teaching to join the Office in April 1940. Before the end of that year he became an independent forecaster at Headquarters No. 11 Group, RAF Uxbridge, and started on a career during the whole of which he has been closely associated with forecasting, especially for aviation. During the latter part of the war he served in the Second Tactical Air Force and then in British Armed Forces Overseas, Germany. After demobilization he returned to Germany as a forecaster until late 1950.

For 14 years he was a senior forecaster at London/Heathrow Airport, receiving substantive promotion to Principal Scientific Officer in 1952. This period saw a great expansion in civil aviation, and Mr Sugden played an active part in the development of forecasting techniques for transatlantic flights.

In November 1964 he turned from forecasting to administration when he took charge of the Main Meteorological Office at the Air Traffic Control Centre, Uxbridge. His aptitude for this type of work led to his posting to the civil aviation section of the Public Services Branch at the Headquarters of the Meteorological Office in Bracknell. Here he maintained excellent relations with the various civil aviation authorities and represented the United Kingdom at numerous meetings and Working Groups of the International Civil Aviation Organization.

On 1 January 1971 Mr Sugden was promoted to Senior Principal Scientific Officer to take charge of the Public Services Branch, where his responsibilities included the weather centres and meteorological services to industry and the public as well as civil aviation. He continued to be much involved in international matters; in the past year he was the United Kingdom delegate at a World Meteorological Organization Commission for Aeronautical Meteorology session in Montreal, and he took part in difficult negotiations at several meetings in Europe concerning the future of ocean weather stations.

We all wish Mr and Mrs Sugden many years of happy retirement.

M. H. FREEMAN

Remote Sensing Society conference

The Remote Sensing Society held its first general conference on 17–19 September 1974 at the University of Aston, Birmingham. The conference discussed the evaluation of the application of space platforms, resource surveys, remote sensing of the environment and remote-sensing data processing. A few papers were relevant to the interdisciplinary branches of applied meteorology such as agricultural meteorology.

REMOTE SENSING SOCIETY PRESS RELEASE

Comparisons of rainfall at Kew

Comparisons of rainfall measured at Kew indicate that, compared with the gravimetric rain-gauge,* the standard 5-inch rain-gauge and the World Meteorological Organization reference pit gauge undercollect by about 5 per cent and 2 per cent respectively. A detailed paper on these comparisons will be published shortly.

* CRAWFORD, S. G.; A recording gravimetric rain-gauge—towards an absolute instrument. *Met Mag, London*, 101, 1972, pp. 368–374.

Automated weather radar display

A system developed under the auspices of the Weather Radar Planning Group for digitizing weather radar information, transmitting it in real-time over an ordinary telephone line, and displaying it on a colour television screen with different colours representing different rates of rainfall was successfully demonstrated in the Central Forecasting Office on 12, 13 and 14 March 1974.

For an article on this subject see the June 1974 issue of *Weather*;* a colour photograph appears on the cover.

The PDP 11/40 mini-computer

The Digital Equipment Corporation PDP 11/40 mini-computer, has been delivered to the Meteorological Office Headquarters and has passed its technical trials.

The PDP 11/40 was acquired primarily to convert data recorded in non-standard forms into media acceptable to the main computer installation (currently an IBM 360/195). This is already being done for certain climatological data which are experimentally being recorded automatically on special magnetic-tape cassettes. The new Mk 3 radiosonde will produce much more detailed data than the existing Mk 2b; summaries will be transmitted direct to the Telecommunications Branch for operational use and the full data will be recorded on magnetic-tape cartridges which will be handled by the PDP 11/40.

The collection of data in computer-readable form eliminates chores which otherwise have to be performed manually (e.g. writing down the figures and keying them) and makes the data more quickly available to the user. It is cheaper to record the data in simple, non-standard form and then to convert, rather than to record in a form directly compatible with the main computer.

The PDP 11/40 has been equipped with a wide range of peripherals (e.g. visual display unit and electrostatic printer/plotter) to allow it to handle a variety of experimental problems. Perhaps one of the most interesting experiments is the design of a computer-controlled terminal that could give main meteorological offices, and perhaps outstations, direct access to the data held in the computer at Bracknell and the ability to display and manipulate the data as they choose.

It is intended that the PDP 11/40 should be used as an experimental test-bed for any application which could require a dedicated small computer. In comparison with larger computers it is relatively simple to add new devices to this computer and to deal with events as they happen, e.g. on-line instrument control and data acquisition.

OBITUARIES

It is with regret that we have to record the death of Mr G. Doherty, Senior Scientific Officer, Pitreavie on 14 June 1974, of Mr J. McStuart, Scientific Officer, London/Heathrow Airport on 28 June 1974 and of Mr I. Keenan, Assistant Scientific Officer, Masirah on 30 June 1974.

* TAYLOR, B.C. and BROWNING, K.A.; Towards an automated weather radar network. *Weather, London*, 29, 1974, pp. 202-216.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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AN ASSESSMENT OF THE USEFULNESS OF SOME SNOW PREDICTORS

By C. A. S. LOWNDES, A. BEYNON and C. L. HAWSON

Summary. The probability of snow is obtained for different values of four predictors, based on observations made at 11 stations in the Gloucester group. The predictors are (a) the 1000-850-mb adjusted thickness, (b) the height of the dry-bulb freezing level, (c) the height of the wet-bulb freezing level, and (d) the 1000-900-mb adjusted thickness. The probabilities obtained for predictors (a) and (b) are compared with those given by Boyden. The success obtained at the Gloucester group stations in forecasting predictors (a), (b) and (c) is indicated and the effect of the forecasting errors on the performance of each predictor is assessed. Similarly, the success obtained by the 10-level atmospheric model on a fine mesh in forecasting predictor (d) is indicated together with the effect of the associated forecasting errors on the performance of this predictor. The comparative efficiency of the predictors in forecasting snow is assessed. A method is given for adjusting the 1000-900-mb thickness to allow for surface pressure and station height.

Introduction. Figure 1 shows the locations, indicated by solid circles, of 11 stations in the Gloucester group which took part in an investigation into the usefulness of various snow predictors during the winters of 1966-67, 1967-68 and 1969-70. The predictors were (a) the 1000-850-mb thickness, adjusted for sea-level pressure and station height as described by Boyden,¹ (b) the height of the dry-bulb freezing level above the station and (c) the height of the wet-bulb freezing level above the station. Values of all three predictors were estimated for each station for 00 GMT and 12 GMT. If precipitation of any type was observed within 6 hours either side of these times, the values and the precipitation type were extracted for discrimination analysis. If, however, more than one type of precipitation occurred during a period, then the period was excluded unless it was clear that one type was more closely associated with the middle of the period than the other(s). Forecast values of the three predictors 12 hours ahead from 00 GMT and 12 GMT were also obtained for seven of the 11 stations. The observations of precipitation type and the actual and forecast values of the predictors were obtained as a daily routine. Six of the stations were subsidiaries, observing at hourly intervals, and five, mainly the high-level stations, were auxiliaries, observing at 3-hourly intervals. The auxiliary stations provided observations of precipitation type only, the actual and forecast values of the three predictors for these stations being obtained by some of the subsidiary stations and the main meteorological office at Gloucester.

(Note: throughout the investigation, observations of drizzle were treated as rain.)

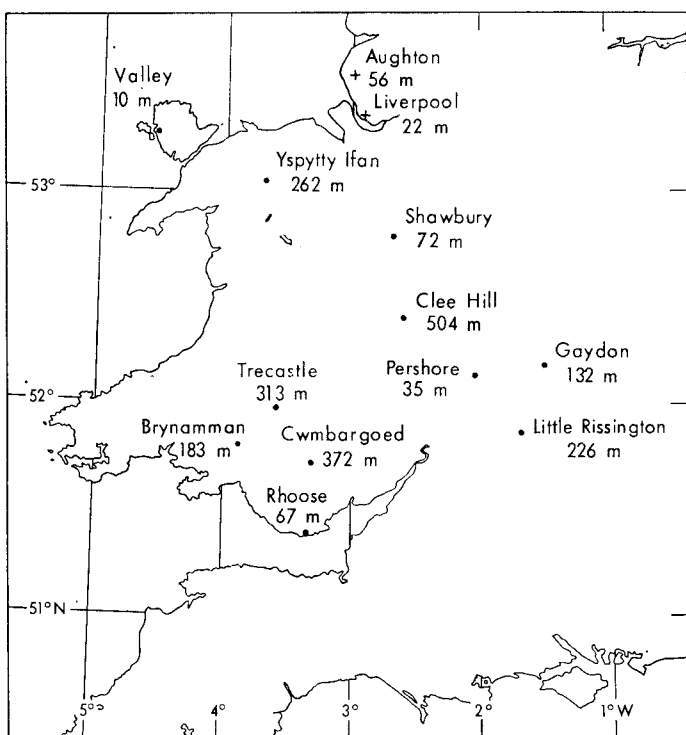


FIGURE 1—LOCATION OF STATIONS

The object of the investigation was primarily to find values of the three predictors associated with various probabilities of precipitation being in the form of snow over hilly terrain, and to find out whether, for the first two predictors, these values differ in any systematic way from those given by Boyden.¹ (The comparison cannot be made for the wet-bulb freezing level since Boyden did not assess this predictor, having deduced that humidity is usually unimportant in considering the probability that snow will melt. On the other hand, other writers such as Lumb² have stressed the importance of the wet-bulb freezing level as a snow predictor.) Secondly, the aim was to investigate the success obtainable in forecasting the values of the predictors, the effect of forecast errors on their performance, and to determine whether any improvements to the forecasting techniques could be suggested in the light of added experience. Because of the relatively small number of occasions of moderate to heavy snow of any duration it was decided to include all reported occasions of snow in the investigation. Furthermore, since a good deal of the wintry precipitation over the high ground of Wales is showery in character, it was decided to distinguish between showery and non-showery precipitation. The number of snow occasions, including both showery and non-showery, ranged from 108 at Ysppyty Ifan to 28 at each of the three lowest stations Rhooose, Pershore and Valley. Overall, the precipitation occasions totalled 579 of snow, 101 of sleet and more than 1400 of rain. By use of the same basic data, the investigation was

later extended to include an assessment of the 1000–900-mb thickness, adjusted for sea-level pressure and station height as indicated on page 355, as a snow predictor.

The 1000–850-mb adjusted thickness as a predictor. Figure 2 shows the probability of rain, sleet* and snow for various values of the 1000–850-mb adjusted thickness for occasions of non-showery precipitation. The probabilities are based on the nine inland stations, Clee Hill, Cwmbargoed, Trecastle, Yspytty Ifan, Little Rissington, Brynamman, Gaydon, Shawbury and Pershore. The two coastal stations Valley and Rhoose are not included since it is thought likely that different criteria would apply to these stations. The curves were drawn to give a smooth fit to the points which had themselves been subjected to smoothing. This smoothing was carried out by taking 5-term running means of the percentage frequency of occurrence of each of the three categories over 1-gpm bands of the adjusted 1000–850-mb thickness. The results were plotted at the mid point of the 5-gpm thickness range. The pecked line shows the effect on the snow probability of the errors made by the Gloucester group of stations in forecasting the thickness 12 hours ahead (see pages 352–353). Probability curves were drawn in the same way for occasions of showery precipitation.

Table I shows that the corresponding values for non-showery and showery precipitation are in close agreement and ‘Student’s’ *t*-tests indicate that all the apparent differences could readily arise by accident of sampling.

The critical values obtained by Boyden¹ which were based on observations from all the radiosonde stations in the British Isles are also shown. The Boyden figures are not strictly comparable because when computing the probabilities of snow he counted an occurrence of sleet as half to snow and half to rain.

TABLE I—VALUES OF THE 1000–850-mb ADJUSTED THICKNESS IN GEOPOTENTIAL METRES CORRESPONDING TO DIFFERENT PROBABILITIES OF SNOW, DISTINGUISHING BETWEEN NON-SHOWERY AND SHOWERY PRECIPITATION (NOT TAKING INTO ACCOUNT THE EFFECT OF FORECAST ERRORS BUT INCLUDING THE EFFECT OF ERRORS IN ESTIMATING THE BASIC THICKNESS DATA)

	Percentage probability of snow				
	90	70	50	30	10
			<i>geopotential metres</i>		
1000–850-mb adjusted thickness for non-showery precipitation	1282 (1283)	1289 (1291)	1293 (1294)	1296 (1298)	1301 (1303)
1000–850-mb adjusted thickness for showery precipitation	1281 (1283)	1290 (1291)	1293 (1294)	1295 (1297)	1299 (1301)
1000–850-mb adjusted thickness (Boyden)	1281	1290	1293	1298	1303

Notes: (a) Values adjusted to make them comparable with those obtained by Boyden are shown in brackets.

(b) A change of 1 gpm in the 1000–850-mb thickness corresponds to a change of 0.21 degC in the mean temperature of the layer.

* The term sleet is commonly used in this country to describe precipitation of snow and rain (or drizzle) together, or of snow melting as it falls, but it has no agreed international meaning.

The values shown in brackets are those for the present investigation adjusted to make them comparable with the Boyden values from which they differ on average by less than 1 gpm. 'Student's' *t*-tests again indicate that all the apparent differences could readily arise by accident of sampling. The close agreement with Boyden's values is a little surprising because Boyden used instantaneous and simultaneous values as observed at radiosonde stations, whereas for the present investigation, results are based on a relationship between precipitation in a 12-hour period and estimated values of the predictor. Thus the errors in the basic data of the present investigation should be greater than those in Boyden's data. The effect of unbiased errors on the probability curves should be to degrade the apparent performance relative to the optimum performance in a similar way to that in which errors in forecasting the predictor degrade the apparent performance (see pages 352-353). Consequently, relative to the optimum performance of the predictor, the probability values in both investigations should already be changed in the same directions as those shown in Figure 2 for the effect of forecasting errors relative to the apparent probability

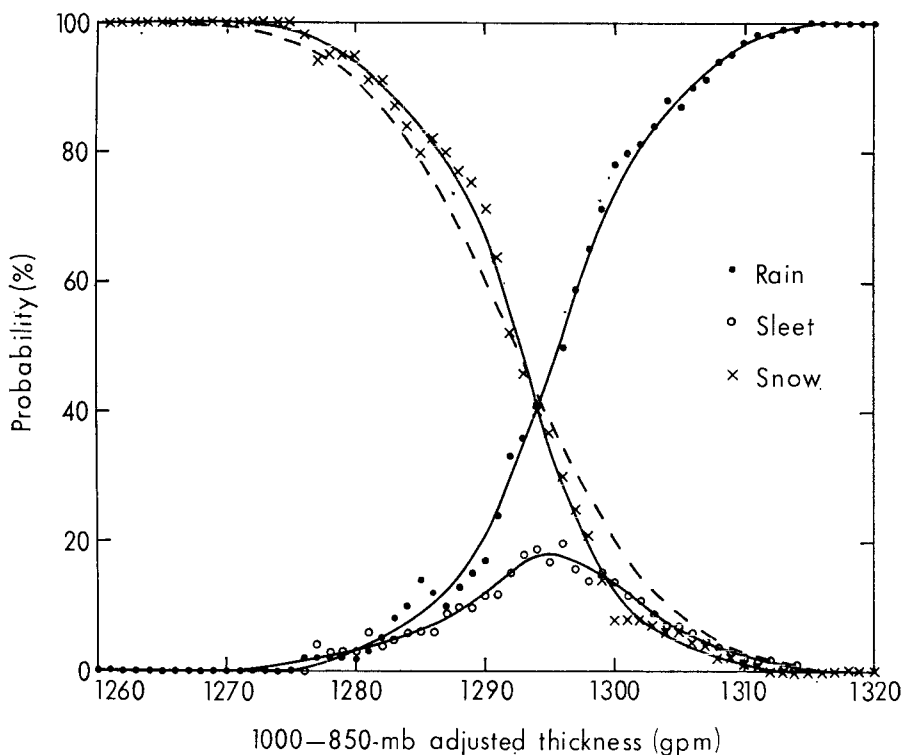


FIGURE 2—PROBABILITY OF RAIN, SLEET AND SNOW FOR VARIOUS VALUES OF THE 1000-850-mb ADJUSTED THICKNESS

The curves are based on occasions of non-showery precipitation at nine inland stations. The pecked line shows the effect on the snow probability of errors in 12-hour forecasts of the thickness made by the Gloucester group of stations.

values. This degradation of performance should be greater for the present investigation than for Boyden's. The effect should be small for the 50 per cent values, tend to lower the apparent thickness for the high probabilities and tend to increase them for low probabilities. Perhaps the close agreement with Boyden's results indicates that the errors involved in estimating the thickness were small.

Probability curves were also prepared for non-showery and showery precipitation combined, but a distinction was drawn between the four highest and five lowest inland stations. Only small, non-significant differences emerged. This indicates that the Boyden correction technique for adjusting the 1000–850-mb thickness for station height works satisfactorily. Similar studies were carried out for the other predictors. For the 1000–900-mb adjusted thickness the differences were again not significant but for the two freezing levels the results were inconclusive.

For non-showery and showery precipitation combined, if snow is forecast when the 1000–850-mb adjusted thickness is correctly forecast as 1293 gpm or less (1293 gpm being the thickness corresponding to a 50 per cent probability of snow) the percentages of successful forecasts for each of the nine inland stations range from 75 to 90 per cent and the successful forecasts represent 80 to 90 per cent of the total snow occasions at each station. For the two coastal stations, Rhooose and Valley, the percentages of successful forecasts are lower, ranging from 60 to 65 per cent, representing 80 per cent of the total snow occasions at both stations. This reduced success is not unexpected at these stations where the warming effect of the sea may turn snow into sleet at critical temperatures. Because of the small sample of data for Rhooose and Valley alone, it is not possible to obtain realistic probability curves for these stations. However, the data suggest that the critical value below which rain is unlikely is about 1290 gpm. Sleet was reported at Rhooose in non-showery situations with thickness values as low as 1280 gpm.

The height of the dry-bulb freezing level above the station as a predictor. Figure 3 shows the probability of rain, sleet and snow for various values of the height of the dry-bulb freezing level above the station for occasions of non-showery precipitation. The probabilities are based on the nine inland stations. The curves were drawn to give a smooth fit to the points which had themselves been subjected to smoothing. This smoothing was carried out by taking 11-term running means of the percentage frequency of occurrence of each of the three categories over 1-mb bands of the height of the freezing level. The results were plotted at the mid point of the 11-mb height range. However, this smoothing technique was not adequate for freezing levels below 6 mb because the occasions recorded as 'zero', which represented a large proportion (about 50 per cent) of the snow occurrences, included many associated with negative surface temperatures. On most of these 'zero' occasions, representative heights for the freezing level would have been negative. In the absence of detailed information, various methods of using the data to define the snow probability curve in the 80 to 100 per cent region were tried, including progressively reducing the smoothing interval and also using skew intervals. Each method resulted in obvious discontinuities and was unsatisfactory. In the circumstances, Little Rissington, whose data were accessible and whose station height is about midway between the highest and lowest of the nine

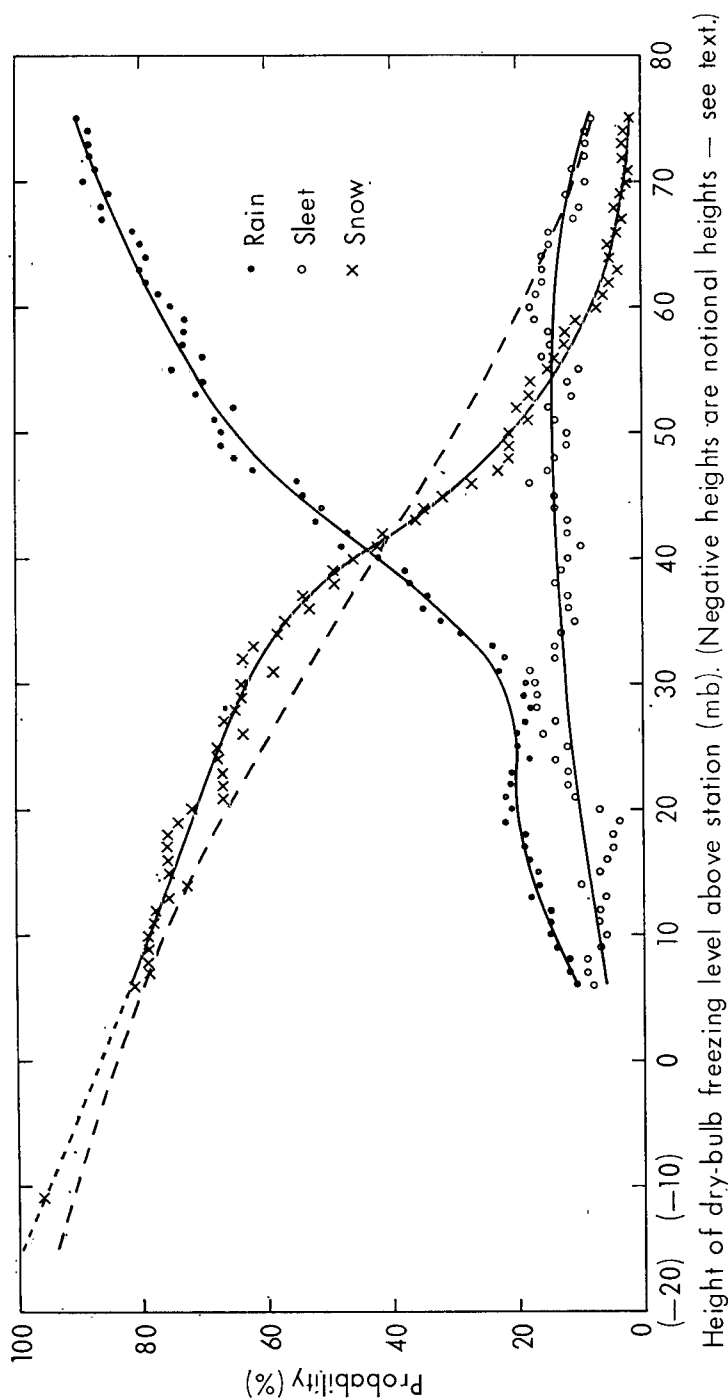


FIGURE 3.—PROBABILITY OF RAIN, SLEET AND SNOW FOR VARIOUS VALUES OF THE DRY-BULB FREEZING LEVEL

The curves are based on occasions of non-showery precipitation at nine inland stations. The pecked line shows the effect on the snow probability of errors in 12-hour forecasts of the height made by the Gloucester group of stations obtained for all forecasts; the corresponding line obtained when forecasts associated with freezing-level heights of 'zero' were excluded is almost the same.

inland stations, was chosen for further examination. Surface dry-bulb temperatures were obtained for the 24 occasions when the freezing level was recorded as 'zero'. All but one were snow occasions and the average surface temperature was -0.6°C . Assuming a notional lapse rate below ground similar to that adopted from Figure 1 of Boyden,¹ namely $0.055^{\circ}\text{C}/\text{mb}$, this suggests roughly a 96 per cent snow probability at an average notional freezing level of -11 mb. This plot of 96 per cent at -11 mb was then used to extrapolate the snow probability curve in the 80 to 100 per cent region, shown dotted in Figure 3.

The pecked line shows the effect on the snow probability of the errors made by the Gloucester group stations in forecasting the height of the freezing level 12 hours ahead (see pages 352-353). Probability curves were drawn in the same way for showery precipitation.

Table II shows that the corresponding values for showery precipitation tend to differ more for high than for low probability values and are on average 4 mb higher than those for non-showery precipitation which is equivalent to a change in temperature of about 0.2°C at a level. 'Student's' *t*-test indicates that this apparent difference could readily arise by accident of sampling. The values in brackets are those for the present investigation adjusted to make them comparable with the Boyden values. The corresponding values for both showery and non-showery precipitation are on average 6 mb higher than the Boyden values which is equivalent to a change in temperature of about 0.3°C at a level. 'Student's' *t*-test indicates that the difference is statistically significant. For the reasons discussed on pages 343-345, the effect of unbiased errors in the data used for the present investigation relative to the errors in the Boyden data would be expected, for the present investigation, to lower the apparent heights for high probabilities and to increase them for low probabilities. This effect cannot therefore account for the differences found in the values for the higher probabilities between the present investigation and that of Boyden.¹ However, the estimates of freezing level for the present investigation relate

TABLE II—VALUES OF THE HEIGHT OF THE DRY-BULB FREEZING LEVEL ABOVE THE STATION IN MILLIBARS CORRESPONDING TO DIFFERENT PROBABILITIES OF SNOW, DISTINGUISHING BETWEEN NON-SHOWERY AND SHOWERY PRECIPITATION (NOT TAKING INTO ACCOUNT THE EFFECT OF FORECAST ERRORS BUT INCLUDING THE EFFECT OF ERRORS IN ESTIMATING THE BASIC DRY-BULB FREEZING-LEVEL DATA)

	Percentage probability of snow				
	90	70	50 <i>millibars</i>	30	10
Height of dry-bulb freezing level for non-showery precipitation	—4*	22 (29)	38 (41)	46 (49)	58 (67)
Height of dry-bulb freezing level for showery precipitation	4	30 (38)	41 (45)	48 (51)	58 (63)
Height of dry-bulb freezing level (Boyden)	12	25	35	45	61

Notes: (a) Values adjusted to make them comparable with those obtained by Boyden are shown in brackets. For the 90 per cent probability it was not possible to make this adjustment.

(b) By use of Figure 1 of Boyden¹ a change of freezing level by 1 mb is taken to be equivalent to a change in temperature of 0.055°C at a level.

* Notional height (see text).

mostly to high-level stations but were based on the network of radiosonde stations which are at relatively low levels. Because low-level air is cooled by ascent over high ground and the height of the freezing level above mean sea level is thereby usually reduced, it is possible that the freezing-level estimates were affected by a small positive bias which could account for the differences between the two investigations.

For non-showery and showery precipitation combined, if snow is forecast when the height of the dry-bulb freezing level above the station is correctly forecast as 40 mb or less (40 mb being the height corresponding to a 50 per cent probability of snow) the percentages of successful forecasts for each of the nine inland stations range from 70 to 90 per cent and the successful forecasts represent 80 to 95 per cent of the total snow occasions at each station. For the two coastal stations, Rhoose and Valley, the percentages of successful forecasts are lower, ranging from 55 to 60 per cent, the successful forecasts representing 85 to 95 per cent of the total snow occasions at each station. However, if a critical value of 30 mb instead of 40 mb is used for Valley, the percentage of snow forecasts correct improves to 75 per cent representing 80 per cent of the total snow occasions at Valley. No such conclusion can be drawn from the data for Rhoose where the forecast failures are mainly associated with non-showery situations, for which rain and sleet are reported on most occasions with heights between 10 mb and 40 mb.

The height of the wet-bulb freezing level above the station as a predictor. Probability curves were drawn, as described in the previous section, based on the height of the wet-bulb freezing level above the station. Figure 4 shows the curves for non-showery precipitation. As with the dry-bulb freezing level, the smoothing technique was not adequate for freezing levels below 6 mb and recourse was again made to surface observations at Little Rissington. Surface wet-bulb temperatures were obtained for the 40 occasions when the freezing level was recorded as 'zero'. All but two were snow occasions and the average surface wet-bulb temperature was -0.7°C , suggesting roughly a 95 per cent probability at an average notional freezing level of -13 mb. This plot of 95 per cent at -13 mb was then used to extrapolate the snow probability curve in the 60 to 100 per cent region, shown dotted in Figure 4. The pecked lines again show the effect of 12-hour forecast errors made by the Gloucester group stations on the snow probabilities (see pages 352–353).

Table III shows that the critical values for showery precipitation are on average 4 mb higher than those for non-showery precipitation which is equivalent to a change in temperature of about 0.2°C at a level. 'Student's' *t*-test indicates that this apparent difference could readily arise from sampling. A similar result was obtained earlier for probabilities based on the height of the dry-bulb freezing level.

For non-showery and showery precipitation combined, if snow is forecast when the height of the wet-bulb freezing level is correctly forecast as 10 mb or less (10 mb being the height corresponding to a 50 per cent probability of snow) the percentages of successful forecasts for each of the nine inland stations and Valley range from 75 to 85 per cent and the successful forecasts represent 80 to 90 per cent of the total snow occasions at each station. The coastal station Rhoose shows the lowest forecast success of 60 per cent, representing 75 per cent of the total snow occasions at the station.

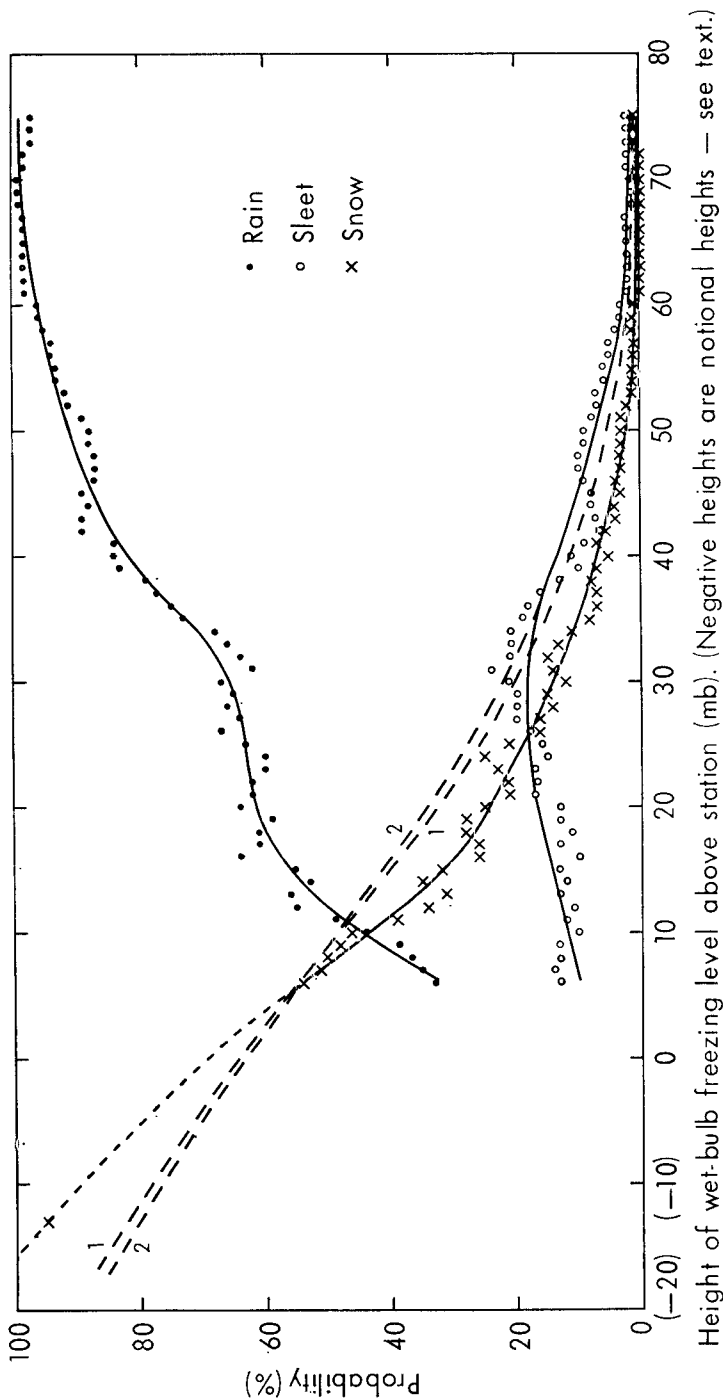


FIGURE 4.—PROBABILITY OF RAIN, SLEET AND SNOW FOR VARIOUS VALUES OF THE HEIGHT OF THE WET-BULB FREEZING LEVEL

The curves are based on occasions of non-showery precipitation at nine inland stations. The pecked lines show the effect on the snow probability of errors in 12-hour forecasts of the height made by the Gloucester group obtained (1) for all forecasts and (2) when forecasts associated with freezing-level heights of 'zero' were excluded.

TABLE III—VALUES OF THE HEIGHT OF THE WET-BULB FREEZING LEVEL ABOVE THE STATION IN MILLIBARS CORRESPONDING TO DIFFERENT PROBABILITIES OF SNOW, DISTINGUISHING BETWEEN NON-SHOWERY AND SHOWERY PRECIPITATION (NOT TAKING INTO ACCOUNT THE EFFECT OF FORECAST ERRORS BUT INCLUDING THE EFFECT OF ERRORS IN ESTIMATING THE BASIC WET-BULB FREEZING-LEVEL DATA)

	Percentage probability of snow				
	90	70	50 <i>millibars</i>	30	10
Height of the wet-bulb freezing level for non-showery precipitation	—10*	0	7	16	35
Height of the wet-bulb freezing level for showery precipitation	—6*	7	13	20	34

Notes: (a) Boyden did not examine the use of the height of the wet-bulb freezing level as a snow predictor.

(b) By use of Figure 1 of Boyden¹ a change of freezing level by 1 mb is taken to be equivalent to a change in temperature of 0.055 degC at a level.

* Notional height (see text).

Forecasting the three predictors at the Gloucester group stations.

The forecasters in the Gloucester group were given a free hand in forecasting the values of the three predictors for 12 hours ahead. In general, advection techniques were used to forecast the 1000–850-mb adjusted thickness. Attempts were made to advect thickness with the surface gradient wind, the 900-mb wind, the 850-mb wind and the 1000–850-mb thermal wind and various fractions of these winds as well as by extrapolation.

Freezing levels were forecast by modifying the upper-air soundings felt to be most representative of the air expected to affect the various stations. At no station were methods found which gave a consistently high degree of success. As was to be expected, the greatest errors occurred during periods of rapid change of air mass when accuracy was most essential. The highest forecast accuracy was found during periods of little change, e.g. February 1968. Table IV shows the percentage of occasions when the error in the forecast of the 1000–850-mb adjusted thickness was 5 gpm or less and 3 gpm or less, and the percentage of occasions when the error in the forecast of the freezing levels was 20 mb or less and 10 mb or less. The standard deviations of normal distributions which would be associated with the average values are shown at the foot of the table. (For the freezing-level forecasts, departures from normal error distributions would be associated with the practice of classifying freezing-level heights as 'zero' when surface temperatures were negative. No attempt was made to allow for this abnormal distribution.)

The average values in this process are simple averages treating each station's results as independent values of equal weight, despite the wide discrepancies in the number of forecasts involved. Alternative methods of averaging might have been used, e.g. by giving weight to stations according to the number of forecasts or by excluding the coastal stations, but the differences between the stations' results are a little greater than would be expected from consideration of the statistical standard error of each result, so simple unweighted averaging was chosen.

At all five inland stations, the percentage of errors less than 20 or 10 mb is less for the dry-bulb freezing level than for the wet-bulb freezing level so that the choice does not affect their relative standing.

TABLE IV.—PERCENTAGE SUCCESS IN FORECASTING SNOW PREDICTORS 12 HOURS AHEAD AT STATIONS IN THE GLOUCESTER GROUP DURING THE WINTERS OF 1966-67 AND 1967-68

Station	1000-850-mb Number of forecasts	adjusted thickness Percentage of forecast errors ≤ 5 gpm	≤ 3 gpm	Number of forecasts	Dry-bulb freezing level Percentage of forecast errors ≤ 20 mb	Percentage of forecast errors ≤ 10 mb	Number of forecasts	Wet-bulb freezing level Percentage of forecast errors ≤ 20 mb	Percentage of forecast errors ≤ 10 mb
Treacastle	466	59	41	504	55	33	501	63	43
Yspyty Ifan	465	59	42	427	54	33	429	61	44
Rissington	89	54	38	87	64	41	87	75	61
Gaydon	143	60	38	52	58	46	61	72	62
Shawbury	39	67	46	39	69	51	39	74	59
Rhoose*	113	64	50	110	63	40	110	54	42
Valley*	85	74	53	76	74	46	76	70	47
All stations	1400	62	44	1295	62	41	1303	67	51
Standard deviation (SD) of error		5.7 gpm	5.2 gpm		22.7 mb (24.0)	18.5 mb (20.5)		21.0 mb (24.0)	14.5 mb (17.5)
Representative SD of error			5.5 gpm		21 mb (22)			18 mb (21)	
Representative SD converted to equivalent temperature units (kelvins)		1.1			1.1 (1.2)			1.0 (1.2)	

* Coastal stations.

Note: Values in brackets show the standard deviation of error when forecasts associated with 'actual' freezing-level heights of 'zero' were excluded.

Because forecasts of freezing levels would be subject to smaller errors when the freezing level is 'zero' than when it is above ground level, the standard deviation of the forecast errors when all forecasts are included should be less than for forecasts when the freezing level is above ground. A separate analysis of forecast errors for the freezing levels was therefore made excluding occasions of 'zero' height. Results of this analysis are shown in brackets in Table IV. They show that the apparent slightly lower standard deviation of error in forecasting the height of the wet-bulb freezing level becomes negligible when 'zero' heights are excluded. There is practically no difference in the accuracy of forecasting the three predictors when the freezing levels are above zero.

The effect of the increased forecast errors in these circumstances would be to further degrade the overall performance of the two freezing-level predictors shown by the pecked lines in Figures 3 and 4. The further degraded performance for the wet-bulb freezing level is shown as a second pecked line in Figure 4, representing an increase in the standard deviation of error from 18 mb to 21 mb. The corresponding line for the dry-bulb freezing level representing an increase in the standard deviation of error from 21 mb to 22 mb is very close to the pecked line in Figure 3 and cannot be distinguished from it.

The effect of forecasting error on predictor performance. Even a predictor which is completely efficient as a snow discriminant, i.e. one for which the probability of snow changes discontinuously from 100 per cent to 0 per cent across some specific value, would be quite useless as a predictor if it could not be forecast with sufficient accuracy. In order to assess a discriminant as a predictor in practice, it is necessary to consider the effect of errors made in forecasting the discriminant on the snow probability curves. To achieve this, the following procedure was used (which implicitly assumes that the errors involved in estimating the data are small in relation to the other errors involved, i.e. in forecasting and the true performance of the predictor):

- (a) For each predictor and its associated forecast period, a set of 20 errors was constructed to represent a sample of errors with zero mean and a normal distribution whose standard deviation was the same as that of the errors in forecasting the predictor over the period as shown in Tables IV and V.
- (b) The appropriate set of 20 errors constructed in (a) was applied to a selected predictor value to yield 20 predictor values.
- (c) For the predictor values determined in (b) the 20 corresponding snow probability values were read from the basic snow probability curve in Figures 2, 3, 4 or 5, as appropriate.
- (d) These 20 probability values were averaged to yield the required probability associated with the selected value of the predictor.
- (e) Sufficient predictor values were selected to define a curve representing the performance of the predictor under conditions of forecast error, shown as pecked lines in Figures 2 to 5.
- (f) When, as for the 1000–850-mb adjusted thickness, the distribution of the snow probability over the range where it was variable could be closely represented by a normal distribution, the standard deviations representing this distribution and that of the appropriate errors of forecasting were simply compounded. The required performance of the predictor under conditions of forecast error was then determined from a

normal distribution with the compound standard deviation and the original mean. The procedures (a) to (e) could have been used throughout but are more cumbersome to operate than (f).

Note that for forecasting purposes it is more realistic to use snow probabilities from the pecked curves in Figures 2 to 5, i.e. curves which allow for the errors of forecasting, rather than from the basic probability curves, and that these differ from Boyden's values. There is, of course, considerable scatter in individual situations.

The 1000–900-mb adjusted thickness as a predictor. Forecasts of the 1000–900-mb thickness are part of the output of the 10-level atmospheric model on a fine mesh.³ It therefore seemed appropriate to make an assessment of the usefulness of the 1000–900-mb adjusted thickness as a snow predictor, using the same basic data as for the other three predictors and the requisite 1000–900-mb thickness charts which were prepared at Bracknell. The 1000–900-mb thickness values obtained for each station were adjusted as described on page 355. Finally, using the smoothing technique described between pages 343 and 345, probability curves were drawn. Figure 5 shows the curves for non-showery precipitation; the meaning of the pecked lines is given in the following paragraph.

Table V shows the standard of success in forecasting the 1000–900-mb thickness obtained in experiments with the 10-level atmospheric model on a fine mesh.³ The error was taken to be the difference between the forecast thickness for the grid point at about 51.4°N, 01°W and the corresponding actual value at Crawley (51.1°N, 00.2°W). The standard deviations of normal distributions representative of these forecast errors are shown at the foot of Table V. Although these errors apply to forecasts of the ordinary 1000–900-mb thickness, consideration of equation (3) below and the errors made in forecasts of surface pressure using the model (root-mean-square errors of 2.5 mb for 12 hours and 5 mb for 36 hours) indicates that in practice they also apply to forecasts of the 1000–900-mb adjusted thickness. The effect of the forecast errors on the snow probability was obtained as described between pages 350 and 352. One pecked line on Figure 5 shows the effect of the 12-hour forecast error and the other the effect of the 36-hour forecast error. The effect of the 24-hour forecast error is about midway between that of the 12-hour and 36-hour forecast errors.

TABLE V—PERCENTAGE SUCCESS IN FORECASTING THE 1000–900-mb THICKNESS OBTAINED BY THE 10-LEVEL ATMOSPHERIC MODEL ON A FINE MESH FROM APRIL TO JULY 1973

	12-hour forecast		24-hour forecast <i>Percentage of forecast errors</i>		36-hour forecast	
	≤5 gpm	≤3 gpm	≤5 gpm	≤3 gpm	≤5 gpm	≤3 gpm
Average percentage	75	56	71	51	65	42
Standard deviation (SD) of error (gpm)	4.3	3.9	4.7	4.3	5.4	5.5
Representative SD of error (gpm)	4.1		4.5		5.4	
Representative SD converted to equivalent temperature units (kelvins)	1.3		1.4		1.7	

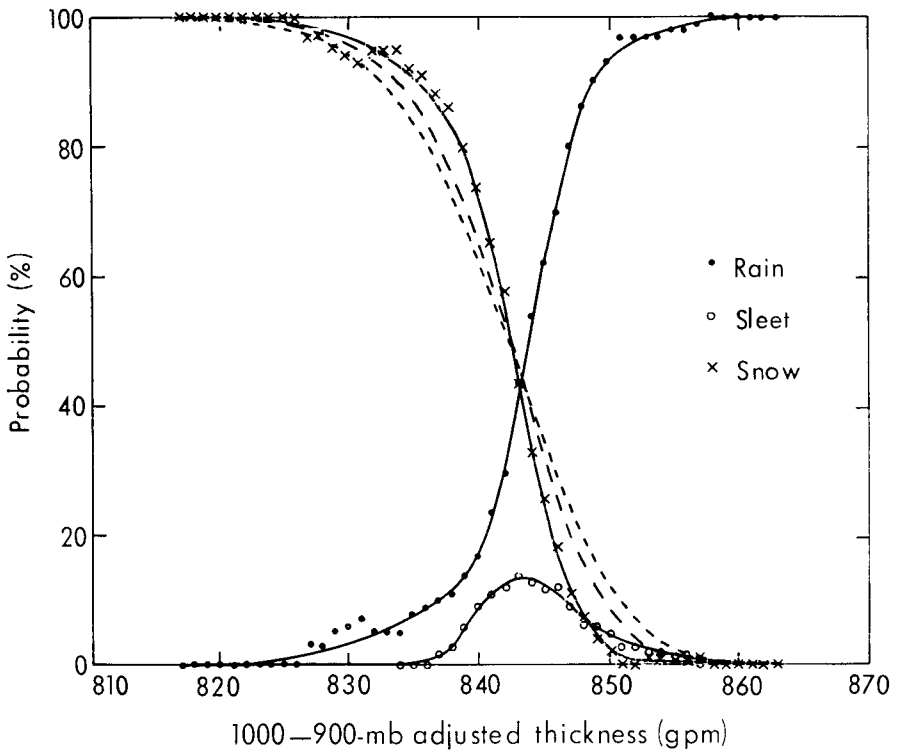


FIGURE 5—PROBABILITY OF RAIN, SLEET AND SNOW FOR VARIOUS VALUES OF THE 1000-900-MB ADJUSTED THICKNESS

The curves are based on occasions of non-showery precipitation at nine inland stations. One peaked line (— — —) shows the effect on the snow probability of errors in experimental 12-hour forecasts of the thickness obtained by use of the 10-level atmospheric model on a fine mesh, and the other peaked line (— · — · —) the effect of errors in the 36-hour forecasts.

Table VI shows that the critical values for showery precipitation are on average 1 gpm higher than those for non-showery precipitation which is equivalent to a change of about 0.3 degC in the mean temperature of the layer. 'Student's' *t*-test indicates that this apparent difference could arise from sampling.

For non-showery and showery precipitation combined, if snow is forecast when the 1000-900-mb adjusted thickness is correctly forecast as 843 gpm or less (843 gpm being the thickness corresponding to a 50 per cent probability of snow) the percentages of successful forecasts for each of the nine inland stations and Valley range from 75 to 85 per cent and the successful forecasts represent 80 to 95 per cent of the total snow occasions at each station. The coastal station Rhooose shows the lowest forecast success of 60 per cent, representing 80 per cent of the total snow occasions at the station. The forecast failures at Rhooose are mainly associated with non-showery situations when sleet is reported with thicknesses as low as 835 gpm.

TABLE VI—VALUES OF THE 1000–900-mb ADJUSTED THICKNESS IN GEOPOTENTIAL METRES CORRESPONDING TO DIFFERENT PROBABILITIES OF SNOW, DISTINGUISHING BETWEEN NON-SHOWERY AND SHOWERY PRECIPITATION (NOT TAKING INTO ACCOUNT THE EFFECT OF FORECAST ERRORS BUT INCLUDING THE EFFECT OF ERRORS IN ESTIMATING THE BASIC THICKNESS DATA)

	90	Percentage probability of snow 70 50 30 10 geopotential metres			
1000–900-mb adjusted thickness for non-showery precipitation	835	841	843	845	847
1000–900-mb adjusted thickness for showery precipitation	835	841	844	846	849

Notes: (a) Boyden did not examine the use of the 1000–900-mb adjusted thickness as a predictor.
(b) A change of 1 gpm in the 1000–900-mb thickness corresponds to a change of 0.32 degC in the mean temperature of the layer.

The adjustment of the 1000–900-mb thickness to allow for surface pressure and station height. Figure 6 shows the relationship between 1000–900-mb thickness and the pressure at the freezing level at Aughton on occasions of sleet at Liverpool Airport. A straight line can be drawn through the points with a slope of 5.7 mb/gpm. At the temperatures involved when sleet occurs, the depth of the atmosphere at low levels corresponding to a pressure difference of 1 mb can be taken as 8 gpm. Then following Boyden's¹ arguments:

Let z in gpm = height of 1000-mb surface above sea level = $z/8$ mb,
 Δz = 1000–900-mb thickness,
 h in gpm = height of the ground above sea level = $h/8$ mb,
 p_g = pressure at the ground in mb, and
 p_f = pressure at the freezing level in mb;

then

$$p_g - p_f = (1000 + z/8 - h/8) - p_f \quad \dots (1)$$

$$= f(\Delta z) + z/8 - h/8,$$

where the function $f(\Delta z)$ is given by Figure 6 as approximately $5.7 (\Delta z - 834)$. Equation (1) may then be written

$$\frac{p_g - p_f}{5.7} + 834 \approx \Delta z + z/46 - h/46 \quad \dots (2)$$

$$\approx \Delta z + \frac{p_0 - 1000}{5.7} - h/46. \quad \dots (3)$$

Of the three terms on the right-hand side of equation (2), $z/46$ is the adjustment to allow for surface pressure, and $h/46$ for the height of the station above sea level. In applying the pressure adjustment over the British Isles it is usually satisfactory to raise the numbering of the 1000–900-mb thickness lines by $(p_0 - 1000)/6$, where p_0 is the general level of sea-level pressure.

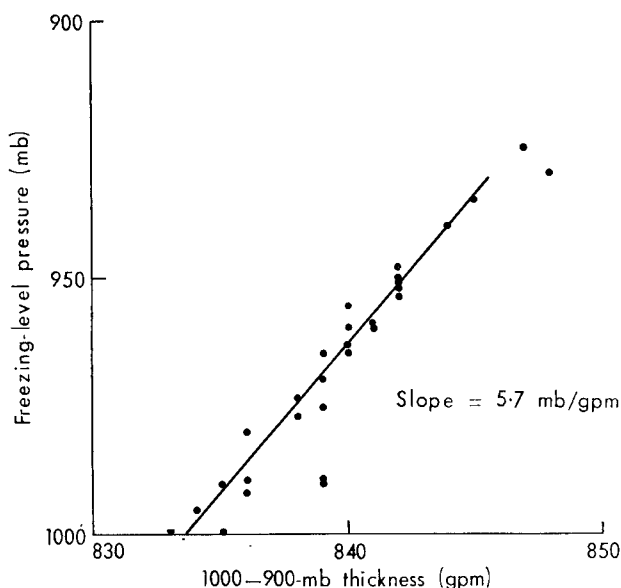


FIGURE 6—RELATIONSHIP BETWEEN THE 1000-900-mb THICKNESS AND THE PRESSURE AT THE FREEZING LEVEL AT AUGHTON ON OCCASIONS OF SLEET AT LIVERPOOL AIRPORT

The comparative efficiency of the predictors in forecasting snow.

Apart from difficulties of forecasting, a predictor can be classified as a good one if the range of the predictor through which the probability of one form of precipitation changes from a high to a low value is small. The range through which the probability of snow changes from 70 to 30 per cent was obtained for each predictor from Figures 2 to 5 and converted to an equivalent change in temperature to facilitate comparison.

Table VII shows the range for each predictor obtained from (a) the original snow probabilities and (b) the probabilities allowing for 12-hour forecast errors. In both cases the value for the wet-bulb freezing level is lower than the values for the other three predictors which are not significantly different from one another.

This suggests that the wet-bulb freezing level is the most efficient of the four predictors and that there is no significant difference between the efficiency of the other three.

This result is partly dependent on the method adopted to construct the curve at the higher probability levels for the wet-bulb freezing level as described between pages 345 and 348. However, other methods of construction which were tried, and considerations of the melting of falling snow, similar to those discussed by Boyden,¹ all suggested higher probabilities of snow for low freezing levels than those adopted and a still smaller range through which the probability of snow changes from 70 per cent to 30 per cent for the wet-bulb freezing-level predictor.

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TABLE VII—RANGE THROUGH WHICH THE PROBABILITY OF SNOW CHANGES FROM 70 TO 30 PER CENT FOR EACH PREDICTOR, EXPRESSED AS AN EQUIVALENT CHANGE IN TEMPERATURE IN KELVINS

Predictor	1000–850-mb adjusted thickness	Dry-bulb freezing level	Wet-bulb freezing level	1000–900-mb adjusted thickness
		<i>kelvins</i>		
Not allowing for forecast errors	1.4	1.3	0.9	1.3
Allowing for 12-hour forecast errors	2.0	1.8	1.4 (1.5)	2.0
Allowing for 36-hour forecast errors	—	—	—	2.4

Note: The figure in brackets shows the value obtained from the second pecked line in Figure 4 which is based on the standard deviation of forecast errors when forecasts associated with 'actual' wet-bulb freezing-level heights of 'zero' were excluded. The use of this figure would not invalidate the suggestion made below that the wet-bulb freezing level is the most efficient of the four predictors.

Conclusions

(a) For nine inland stations in the region of Wales and the West Midlands, Figures 2, 3 and 4 show the probability of rain, sleet and snow corresponding to different values of (1) the 1000–850-mb adjusted thickness, (2) the height of the dry-bulb freezing level, and (3) the height of the wet-bulb freezing level. The effect on the snow probability of errors in 12-hour forecasts of the predictors made by the Gloucester group of stations is shown for all three predictors.

For the same stations, Figure 5 shows the probability of rain, sleet and snow corresponding to different values of 1000–900-mb adjusted thickness. The effect on the snow probability of errors in experimental 12-hour and 36-hour forecasts of the thickness obtained by use of the 10-level atmospheric model on a fine mesh³ is indicated.

(b) For all the predictors, the values corresponding to different probabilities of snow are not significantly different for non-showery and showery precipitation. There is also no significant difference between values for the four highest and five lowest inland stations for the thickness predictors, which suggests that the Boyden correction technique for station height works satisfactorily.

For the 1000–850-mb adjusted thickness, the values corresponding to different probabilities of snow are not significantly different from the values obtained by Boyden.¹ For the height of the dry-bulb freezing level, the values are on average 6 mb higher than the values obtained by Boyden. This difference is statistically significant and a possible explanation is suggested.

(*Note:* Boyden did not examine the use of the wet-bulb freezing level or the 1000–900-mb adjusted thickness as snow predictors.)

(c) If snow is forecast at each of the nine inland stations and at the two coastal stations, Rhoose and Valley, whenever the value of a predictor is correctly forecast to be within the range of values corresponding to 50 to 100 per cent probability of snow, the forecast success obtained is relatively low for Rhoose and Valley except when the wet-bulb freezing level or the 1000–900-mb adjusted thickness is used as the predictor for Valley.

(d) The range through which the probability of snow changes from 70 to 30 per cent, used as a measure of the efficiency of the predictors, suggests that the wet-bulb freezing level is the most efficient predictor of snow and that there is no significant difference between the efficiency of the other three.

(e) A series of 12-hour forecasts of (1) the 1000–850-mb adjusted thickness, (2) the height of the dry-bulb freezing level, and (3) the height of the wet-bulb freezing level made by forecasters of the Gloucester group of stations indicated that there is little difference in the accuracy of forecasting the three predictors when freezing levels are above ground level.

(f) Forecasts of the 1000–900-mb thickness are part of the output of the 10-level atmospheric model on a fine mesh³ and experiments with the model for up to 36 hours ahead show a promising degree of success.

Acknowledgement. The help given by Mr J. Crabtree and Mr C. J. Boyden is gratefully acknowledged.

REFERENCES

1. BOYDEN, C. J.; A comparison of snow predictors. *Met Mag, London*, 93, 1964, pp. 353–365.
2. LUMB, F. E.; The problem of forecasting the downward penetration of snow. *Met Mag, London*, 90, 1961, pp. 310–319.
3. BUSHBY, F. H. and TIMPSON, MARGARET S.; A 10-level atmospheric model and frontal rain. *QJR Met Soc, London*, 93, 1967, pp. 1–17.

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A NOTE ON THE VERTICAL DISTRIBUTION OF RAINDROP-SIZE SPECTRA IN TROPICAL STORM FELICE

By FRANCIS J. MERCERET

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Summary. Foil-impactor measurements from tropical storm Felice give raindrop size distributions which are generally in agreement with the classical formula of Marshall and Palmer. Results indicate that there may be significant spectral differences between measurements taken above cloud base and those taken below as predicted by Mason and Ramanadham.

Introduction. On 15 September 1970 two DC-6 aircraft from the Research Flight Facility of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Miami, Florida, carried airborne foil impactors through tropical storm Felice in the Gulf of Mexico. 'A' Flight stayed mostly at 13 000 ft,* well above cloud base, while 'B' Flight stayed at 1500 ft, or about 500 ft below cloud base, while making the measurements discussed in this paper.

The data, raindrop impressions on aluminium foil, were sized and counted from photographs similar to those described by Merceret.¹ These were grouped into sets small enough to represent a sample over a relatively homogeneous region of the storm (2-km path or less) but large enough to satisfy the criterion for statistical significance suggested by Cornford^{2,3,4} which here required samples of at least 330 impressions. Data not simultaneously meeting both constraints were discarded.

* 1 ft $\approx$ 0.305 m.

Droplet impressions were sorted into diameter categories 250 μm wide, the first being those with diameters $\leq 250 \mu\text{m}$, the next being those with diameters $> 250 \mu\text{m}$ but $\leq 500 \mu\text{m}$ and so on. From the drop counts in each category values for the liquid water content, mean and median droplet sizes, rainfall rate, and spectral parameters were computed for each set. The spectral parameters were the slopes (λ), intercepts (N_0) and correlation coefficients (r) for least-square fits of the form

$$\ln Nd = \ln N_0 - \lambda D,$$

where $Nd(D)$ is the volume number density (m^{-4}) of droplets of diameter $D(\text{cm})$ as described by Merceret.⁵ This form is the same as that used by Marshall and Palmer.⁶

Experimental results. In Felice, the exponential model, though classically applicable at the ground, worked significantly better above the cloud base than below it. Of 92 data sets from 'A' Flight, 85 (92 per cent) showed correlations $r \geq 0.9$ to the exponential form as did 20 (53 per cent) of 38 sets from 'B' Flight. Since an investigation of the exponential distribution was a major motivation for the overall research programme, subsequent investigation was confined to those data sets satisfying $r \geq 0.9$. This may have been over-cautious since most of the remainder satisfied $r \geq 0.75$, but the results, being based on such good fits, may be thus all the more important; even for spectra selected to satisfy $r \geq 0.9$, the standard deviation of the data about the regression line averaged 1.7 times larger below cloud base than above.

The difference is not accounted for by significant differences in the liquid water content of the environments sampled. The liquid water content above the cloud base averaged 0.935 g/m^3 while below the base it averaged 0.930 g/m^3 . On the other hand, not only are the spectra less well correlated to the exponential form below the cloud base, but the intercept of the regression line is quite different. Above the cloud base the intercept N_0 agrees with the classical value within a factor of 3, the mean value being 0.44 of that found by Marshall and Palmer. Below the base the intercept averages 0.095 that of Marshall and Palmer, a factor of 4.61 smaller. Moreover, the mean droplet diameter calculated independently of the least-square fits was 1033 μm above cloud base and 1446 μm below, thus strengthening the inference of a real difference in the spectra in the two regions at the same liquid water content. The possibility of spectral dependence on position with respect to cloud base was predicted in numerical calculations by Mason and Ramanadham⁷ and the experimental result is thus particularly interesting.

Conclusion. The mean droplet-diameter data and the intercepts of the Marshall-Palmer regression lines indicate that in tropical storm Felice the smaller raindrops were depleted below the cloud base while the larger ones contributing most heavily to the liquid water content remained little affected. This resulted in a peaked spectrum having a lower correlation with the exponential form. This is in accord with the prediction by Mason and Ramanadham based on the effect of evaporation during the fall of the droplets.

Because Cornford's criteria were satisfied the phenomenon is not likely to be due to sampling errors, and because the phenomenon is so systematic and marked with respect to cloud base it is unlikely to be a fiction of the instrument.

The amount of data is still small, however, and this should be considered more an indicator for further research than a firm conclusion. Analyses of similar flights in future storms should indicate in more detail and with greater certainty the nature and magnitude of the effect suggested here.

REFERENCES

1. MERCERET, F. J.; A contribution to the measurement of raindrop spectra with airborne foil impactors. *J Appl Met, Lancaster, Pa*, **12**, 1973, pp. 893-895.
2. CORNFORD, S. G.; Sampling errors in measurements of raindrop and cloud droplet concentrations. *Met Mag, London*, **96**, 1967, pp. 271-282.
3. CORNFORD, S. G.; Sampling errors in measurements of particle size distributions. *Met Mag, London*, **97**, 1968, pp. 12-16.
4. CORNFORD, S. G.; The measurement of shower rainfall using an airborne foil impactor. *J Appl Met, Lancaster, Pa*, **7**, 1968, pp. 956-957.
5. MERCERET, F. J.; An extended analysis of raindrop spectra from tropical storm Felice. Washington, U.S. Department of Commerce, NOAA-NHRL, Project Stormfury Annual Report, 1972, Miami, 1973, Appendix 7.
6. MARSHALL, J. S. and PALMER, W. MCK.; The distribution of raindrops with size. *J Met, Lancaster, Pa*, **5**, 1948, pp. 165-166.
7. MASON, B. J. and RAMANADHAM, R.; Modification of the size distribution of falling raindrops by coalescence. *QJR Met Soc, London*, **80**, 1954, pp. 388-394.

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TEMPERATURE DIFFERENCES BETWEEN TWO GROUND-LEVEL SITES AND A ROOF SITE IN SOUTHAMPTON

By J. J. ARMSTRONG
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Summary. In view of the increasing interest in urban meteorological data and the availability of overlapping records from two Park sites and a roof site in Southampton, it was considered that comparisons of daily maximum and minimum temperatures would be of some interest. The findings of an earlier investigation were confirmed and the final results demonstrated that there was surprisingly little difference between conventional and unconventional site exposures.

Introduction. Temperature observations were made daily at 09 GMT at Southampton East Park climatological station from the mid nineteenth century up to 1969 and are usually quoted as the official climatological values for the district. In 1970 the station was moved to Mayflower Park. In the meantime, continuous temperature records became available in 1962 from the roof of the Weather Centre, situated between the two Park sites on a roughly north-south line and in the heart of the city (see Figure 1 for location of sites).

In 1967, D. M. Love¹ produced a preliminary analysis of the temperature differences between East Park and the Weather Centre roof based on two years' observations, 1963-64. This appeared to show that 'no misleading conclusions would be conveyed by comparison of extreme temperatures recorded on the roof site with the appropriate climatological mean or extreme. Neither does it seem unreasonable to assume that, at times of day other than when the extremes occurred, the temperatures would not show any greater variation between the conventional and unconventional exposures'.

This present assessment arises out of the move of the climatological station to Mayflower Park, to a site which differs greatly from the East Park site. Three full years of observations were available, 1970-72, so the East Park analysis was extended by a third year, 1965, partly to confirm the results from 1963-64, but mainly to establish a three-year period for each survey.

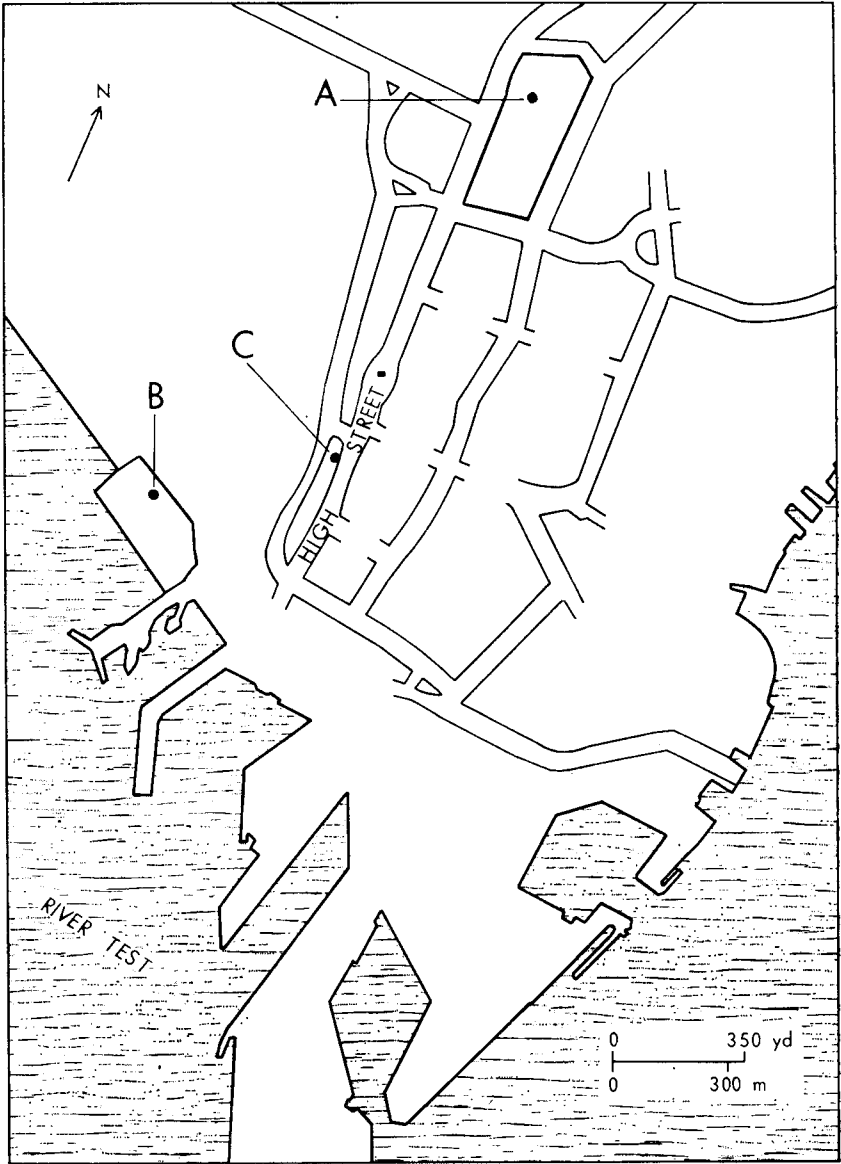


FIGURE 1—MAP SHOWING LOCATIONS OF THREE CLIMATOLOGICAL STATIONS
IN SOUTHAMPTON

A East Park. B Mayflower Park. C Weather Centre.

The sites. The East Park and Weather Centre roof sites were described fully in Love's article but a brief summary is given here for easy reference. East Park (no longer in use) was an orthodox grass-covered enclosure at a

height of 65 ft* above mean sea level. The exposure, while fairly good for an urban site, was not ideal, the enclosure being situated on a slight mound, about 3 ft above the general level, almost completely surrounded by a thick holly hedge 4 ft 6 in high, and with trees in the surrounding park sheltering the site to some extent. At its nearest point, the holly hedge was about 16 ft distant from the thermometer screen.

The Weather Centre roof is asphalt-covered, 33 ft above street level and 61 ft above sea level, and is part of a long, nearly level roof which lies almost north-south. At the south-west corner, just off the main roof, the anemometer lattice tower rises to 16 ft with the retractable mast extending to 30 ft above the site level; about 75 yd* distant to the south-west is a large block of flats, but these are the only significant obstructions. This site and the East Park site are at almost the same height above sea level. The main differences between them are the nature of the underlying surfaces—grass and asphalt—and the more open aspect of the roof site at its height of 33 ft above street level.

The Mayflower Park site is situated directly alongside the River Test, the Park having been established on reclaimed land. The subsoil consists of miscellaneous debris and dredged material and the ground is fairly level, the height of the rain-gauge being 11 ft above mean sea level, and the base of the screen 14 ft 6 in. The enclosure is about 500 ft from the river bank (wall) to the south and separated by a hedge of evergreens (about 3 ft high) from the Docks approach road which extends along the north side of the Park. Insignificant obstructions are a children's playground 200 ft to the south-east and warehouse buildings about 300 ft to the west.

Monthly mean maximum and minimum temperatures. Dealing briefly with East Park and Weather Centre figures (not tabulated), the 1965 means confirmed Love's findings that the Park maxima were almost invariably higher than those recorded at the Weather Centre (the only exceptions being the unusually cold months of January and February 1963). They also confirm that the smallest differences are measured in the winter months. Park minima were invariably lower than those for the roof site, with the smallest differences now being measured in the summer months.

A general assessment therefore is that the diurnal range of temperature was greater at East Park than at the Weather Centre throughout the year by about one to one and a half degrees Celsius, with higher maxima in the summer and lower minima in the winter. The Mayflower-Weather Centre comparison produces results which are perhaps rather more unexpected (Tables I and II).

Annual mean maxima show virtually no difference at all between the sites. Monthly mean differences generally are 0.4 degrees or less throughout the year (apart from 0.7 in September 1972), and they fluctuate either side of zero with, on first assessment, no significant pattern. September 1972 was in fact an exceptionally cool month and the Park mean maximum of 18.0°C was the highest in the area, presumably owing to the very warm water in the nearby River Test. (Outflow from the Marchwood Power Station on the opposite bank of the river and only about one mile away results in river temperatures as high as 22°C in the summer months.)

The minimum temperature records show a slightly larger variation and Mayflower Park temperatures are generally lower, but even here the largest monthly mean difference is only 0.6 degC and the average over the three years is a mere 0.3 degC.

* 1 ft = 0.3048 m; 1 yd = 0.9144 m.

TABLE I—MONTHLY MEAN 24-HOUR MAXIMUM TEMPERATURES

	Mayflower Park	1970 Weather Centre	Difference*	Mayflower Park	1971 Weather Centre	Difference*	Mayflower Park	1972 Weather Centre	Difference*	Three-year mean difference*	Three-year mean difference (East Park minus Weather Centre)
	°C	°C	degC	°C	°C	degC	°C	°C	degC	degC	degC
January	7.9	7.9	0.0	8.1	8.1	0.0	7.5	7.3	-0.2	-0.07	+0.13
February	7.8	7.7	+0.1	8.7	8.8	-0.1	8.3	8.1	-0.2	-0.07	+0.30
March	8.5	8.6	-0.1	9.2	9.2	0.0	12.2	12.3	-0.1	-0.07	+0.70
April	11.2	11.4	-0.2	12.8	12.8	0.0	13.4	13.3	0.1	-0.10	+0.73
May	18.3	18.7	-0.4	17.5	17.6	-0.1	14.8	14.8	0.0	-0.17	+0.81
June	22.4	22.3	-0.1	17.8	17.7	+0.1	15.6	16.0	-0.4	-0.13	+0.73
July	20.3	20.6	-0.3	23.3	23.3	0.0	21.0	21.2	-0.1	-0.13	+0.73
August	21.3	21.6	-0.3	20.5	20.7	-0.2	21.6	21.4	+0.2	-0.10	+0.87
September	19.5	19.9	-0.4	20.7	20.6	+0.1	18.0	17.3	+0.7	+0.13	+0.77
October	15.6	15.6	0.0	16.7	17.0	-0.3	15.6	15.5	+0.1	-0.07	+0.83
November	12.5	12.6	-0.1	10.9	10.8	+0.1	10.8	10.7	+0.1	+0.03	+0.57
December	7.5	7.4	+0.1	9.5	9.5	0.0	10.0	10.1	-0.1	0	+0.40
Year	14.4	14.5	-0.1	14.6	14.7	-0.1	14.1	14.0	0.1		

* Mayflower Park values minus Weather Centre values.
The 24-hour period starts and ends at 09 GMT.

TABLE II—MONTHLY MEAN 24-HOUR MINIMUM TEMPERATURES

	Mayflower Park	1970 Weather Centre	Difference*	Mayflower Park	1971 Weather Centre	Difference*	Mayflower Park	1972 Weather Centre	Difference*	Three-year mean difference*	Three-year mean difference (East Park minus Weather Centre)
	°C	°C	degC	°C	°C	degC	°C	°C	degC	degC	degC
January	3.1	2.8	+0.3	3.4	3.6	-0.2	2.8	3.0	-0.2	-0.03	-0.70
February	1.8	1.4	+0.4	2.1	2.4	-0.3	3.1	3.7	-0.6	-0.17	-0.43
March	1.5	1.3	+0.2	2.5	2.9	-0.4	4.1	4.4	-0.3	-0.17	-0.70
April	4.2	4.1	+0.1	5.2	5.3	-0.1	6.2	6.7	-0.5	-0.17	-0.50
May	9.1	9.5	-0.4	8.4	8.8	-0.4	7.9	8.2	-0.3	-0.37	-0.37
June	12.8	13.0	-0.2	10.1	10.4	-0.3	9.1	9.4	-0.3	-0.27	-0.37
July	12.3	12.4	-0.1	13.7	14.2	-0.5	12.6	13.0	-0.4	-0.33	-0.47
August	13.1	13.2	-0.1	13.7	14.1	-0.4	12.1	12.5	-0.4	-0.30	-0.47
September	11.8	12.1	-0.3	10.5	11.1	-0.6	9.1	9.6	-0.5	-0.47	-0.50
October	8.4	8.0	+0.4	8.7	9.0	-0.3	8.5	8.9	-0.4	-0.10	-0.83
November	6.7	6.4	+0.3	2.9	3.4	-0.5	4.1	4.4	-0.3	-0.17	-0.73
December	2.3	2.4	-0.1	4.9	5.1	-0.2	4.7	5.0	-0.3	-0.20	-1.13
Year	7.3	7.2	+0.1	7.2	7.5	-0.3	7.0	7.4	-0.4		

* Mayflower Park values minus Weather Centre values.
The 24-hour period starts and ends at 09 GMT.

If three-year averages of the monthly mean differences of maximum and minimum temperatures are calculated, graphs of the results (Figures 2 and 3) show a distinct seasonal pattern for the East Park and Weather Centre data with the difference between the maxima increasing markedly from winter to summer, and the difference between the minima showing a noticeable decrease. On the Mayflower Park-Weather Centre graph, the effect is seen to be much less with just a slight increase in maxima differences, winter to summer, but a rather more significant increase in minima differences.

Daily differences of 24-hour maximum and minimum temperatures.

These were also analysed by Love but since the 1965 figures only serve to bear out those already considered there is little point in reprinting the tables. The Fahrenheit scale of temperature was used and the results showed that about 88 per cent of roof maxima fell within the range 0.5 degF above to 2.5 degF below the East Park maxima and nearly 93 per cent of roof minima fell within the range 0.5 degF below to 2.5 degF above the East Park values.

Tables III and IV show quite clearly that an equally close agreement can be expected for the Mayflower Park and roof readings, i.e. 85 per cent of the differences between Park and roof maxima, and 91 per cent of the differences between minima fell within the range plus 0.5 degC to minus 0.9 degC. Although the mean annual and monthly comparisons showed insignificant variation between the two sites, a close study of the daily differences gives

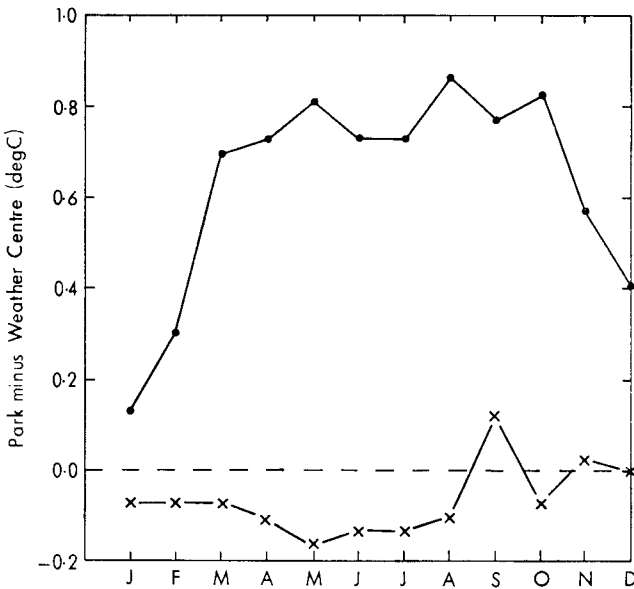


FIGURE 2—DIFFERENCE BETWEEN MONTHLY MEAN MAXIMUM TEMPERATURES RECORDED AT EAST PARK, MAYFLOWER PARK AND SOUTHAMPTON WEATHER CENTRE, 1970-72

· — · East Park.
X — X Mayflower Park.

TABLE III—MONTHLY MEANS OF DAILY DIFFERENCES OF 24-HOUR MAXIMUM TEMPERATURES, 1970-72

<i>Difference* degC</i>	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
	<i>Percentage number of occasions</i>												
More than 1.5	2	1					3	1	3		2		1.0
1.1 to 1.5	2	2	1	2		2	2	3	9	1			2.1
0.6 to 1.0	9	8	6	9	10	2	5	12	12	4	6		7.3
0.1 to 0.5	15	10	24	13	14	18	16	16	16	15	19	5	16.7
0.0 to -0.4	60	66	48	51	42	50	36	33	37	60	58	24	49.3
-0.5 to -0.9	10	10	19	23	25	22	29	26	19	19	13	16	19.3
-1.0 to -1.4	2	2	2	2	9	6	9	9	4	1	1	2	4.1
-1.5 and over		1										2	0.3

* Mayflower Park values minus Weather Centre values. The 24-hour period starts and ends at 09 GMT.

TABLE IV—MONTHLY MEANS OF DAILY DIFFERENCES OF 24-HOUR MINIMUM TEMPERATURES, 1970-72

<i>Difference* degC</i>	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
	<i>Percentage number of occasions</i>												
More than 1.5		1		1				1					0.3
1.1 to 1.5										1		1	0.2
0.6 to 1.0		2			1	1		1		2	2	1	0.8
0.1 to 0.5	18	17	14	6	12	13	11	10	8	3	16	10	11.5
0.0 to -0.4	60	54	58	59	50	66	61	53	47	59	45	60	56.0
-0.5 to -0.9	20	19	18	25	30	17	24	32	26	24	31	23	24.1
-1.0 to -1.4	2	7	7	6	7	1	3	2	18	11	6	3	1.1
-1.5 and over			3	3		2	1	1				2	

* Mayflower Park values minus Weather Centre values. The 24-hour period starts and ends at 09 GMT.

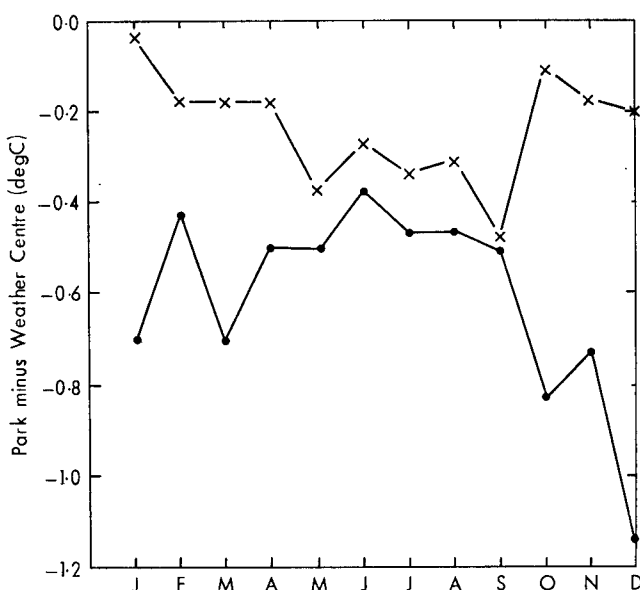


FIGURE 3—DIFFERENCE BETWEEN MONTHLY MEAN MINIMUM TEMPERATURES RECORDED AT EAST PARK, MAYFLOWER PARK AND SOUTHAMPTON WEATHER CENTRE, 1970-72

· ——— · East Park.
X ——— X Mayflower Park.

rather more positive results. The Weather Centre maxima are 0.0 to 0.4 degC higher on almost 50 per cent of occasions and between 0.5 and 0.9 degC on about 19 per cent. However, there is a clear trend for the frequency to increase in the 0.5-0.9 range, at the expense of the other, from March to August with a sudden reversal of the trend in September (Table III). That is, the roof site shows a progressive warming during the spring and high summer, relative to Mayflower Park, but cools very quickly again in September. The 'non-fit' of the month of June is almost certainly due to the fact that this was a particularly cool month in both 1971 and 1972 (maximum temperatures 2-3 degC below normal, minimum temperature 1-2 degC below), and the usual steady monthly rise of mean temperature was seriously affected.

The reasons for these seasonal changes are far from obvious. One explanation could be that the built-up area around the roof site has a warming effect, though this is not borne out by East Park figures which were generally higher than those for the roof. A more probable cause is that sea-breezes setting in during the summer months would affect the Mayflower Park site some time before the roof site and allow the latter to attain a higher maximum. Sea-breeze frequencies would be expected to decrease noticeably during September.

Minimum temperatures (Table IV). Inspection shows the very positive nature of the difference between the sites, the Weather Centre figures being equal to, or higher than, those for Mayflower Park on more than 87 per cent

of occasions. Even so, the difference is mostly less than half a degree. No definite trends can be identified except for some slight indication of more frequent occasions during the winter months (January and February in particular) when Mayflower Park minima were higher than those recorded on the roof. Observations would appear to show that these occurred on occasions when there was a southerly component to the wind, blowing directly off the 'warm' water.

Greater anomalies. An attempt was made to assess the reasons for the larger differences between the two sites, i.e. those in excess of 1 degC both maximum and minimum. No definite pattern(s) emerged from this, but the following points were noted:

- (a) Some large differences of maxima (positive or negative) occurred on showery days—presumably due to the difference in intensity, distribution or time of the showers but with only one observation per day at Mayflower Park this cannot be substantiated.
- (b) Some large anomalies, again both positive and negative, also occurred on days of prolonged moderate-heavy rain.
- (c) Large positive differences of minima (roof higher) were noted when temperatures were rising rapidly around 09 GMT. Two observers are involved so the time difference would not be great, and the rate of rise on the roof was invariably quicker than at Mayflower Park.

Conclusions. The most interesting fact emerging from this dual analysis is that although the East Park temperatures showed a fairly close agreement with those for the Weather Centre, the Mayflower Park readings are even closer. The maximum temperatures show East Park to be warmer than the roof of the Weather Centre which is in turn warmer than Mayflower Park, whereas the minimum temperatures show East Park to be colder than Mayflower Park, which is colder than the roof.

Love argued that the closer agreement between the two sites in Southampton (East Park and the Weather Centre roof) than between those found by Marshall² in London is probably due to the lower height of the building above street level (33 ft against 122 ft) and the lower thermal capacity of the smaller building. As a result of the Mayflower Park comparison it would appear that the thermal capacity of the Weather Centre building has very little effect on the readings obtained (half a degree Celsius or less), and that the extreme temperatures recorded on the roof can be considered to be equally representative of the city as were those recorded on conventional sites. It is also probable that one could assume that at any given time of day the temperatures at the climatological station and on the roof would show an acceptable measure of agreement.

†

REFERENCES

1. LOVE, D. M.; Temperature differences between a ground-level site and a roof site in Southampton. *Met Mag, London*, 96, 1967, pp. 353-356.
2. MARSHALL, W. A. L.; London temperatures. *Met Mag, London*, 77, 1948, pp. 54-59.

AN INVESTIGATION INTO CONSECUTIVE WET WORKING DAYS AT SOUTHAMPTON

By L. P. STEVENS
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Summary. The number of consecutive wet days at Southampton Weather Centre for the 10-year period 1963–72 was analysed to help in the planning of outdoor activities.

Introduction. Numerous requests are received at the Weather Centre for information on rainfall during daylight hours from the construction industries, farmers, market gardeners, sports clubs and organizers of outdoor entertainments, to assist them in planning ahead. An investigation was undertaken by H. V. Foord* using London Weather Centre data and it was considered that a similar study for a place in central southern England close to the coast and centred in one of the major urban development areas would allow for some comparison with the London data for the benefit of designers and planners in industry and commerce.

Although Southampton is at the head of Southampton Water and 10 miles or so from an imaginary line across the base of this inlet, it can be treated more or less as a coastal station as far as rain-bearing frontal systems are concerned. The majority of the most active systems approach from a south-westerly direction and Southampton has little shelter from this quarter. Rainfall data over the 24-hour period are available for Southampton for about 100 years but hyetograms only date from 1963, after the opening of the Weather Centre.

Procedure. A direct comparison with the London Weather Centre analysis was not possible. Foord used the period 1946–71, but detailed rainfall data for Southampton Weather Centre are only available from 1963, so the period used was the decade 1963–72. Also, a 'wet working day' was defined as one with one millimetre or more of rain between 06 GMT and 18 GMT. This period was necessarily selected in order to fit the rainfall readings and although it differs from the 09–18 GMT period used by Foord it probably covers more closely the working day of the construction industry over the part of the year when most work is undertaken.

Frequency of consecutive working days. The analysis of data has been prepared in the same format as Foord's to allow for some comparison. Table I shows the frequencies of single wet working days and sets of consecutive wet working days, as defined above, for each month, and the total frequencies over the 10-year period. However, in order to decide the chances of achieving dry weather on one day by allotting a certain number of consecutive days to a project, sets with a high number of consecutive wet days must be taken to contribute to the sets of lower numbers of consecutive wet days, i.e. three consecutive wet days also count as three single wet days and as two occasions of two consecutive wet days, and so on. These cumulative frequencies are given in Table II for each month, together with the total frequencies for the 10-year period. The cumulative averages are given in Table III, together with the annual averages and standard deviations and the monthly cumulative averages for the whole period.

* FOORD, H. V.; An investigation into consecutive wet working days at London Weather Centre. *Met Mag, London*, 101, 1972, pp. 362–366.

TABLE I—TOTALS OF CONSECUTIVE WET WORKING DAYS, JANUARY 1963 TO DECEMBER 1972

	Consecutive wet working days					
	1	2	3	4	5	6 and over
January	37	11	3	4	0	0
February	24	8	4	1	0	1
March	25	8	6	1	0	0
April	28	6	3	1	1	0
May	38	5	6	1	0	0
June	24	8	3	1	1	0
July	29	5	1	0	0	0
August	25	10	2	0	0	0
September	19	9	3	2	0	0
October	26	9	4	1	0	0
November	29	11	2	0	2	1 (8 days)
December	36	9	4	0	0	1 (8 days)
Total	340	99	41	12	4	3

TABLE II—CUMULATIVE TOTALS OF CONSECUTIVE WET WORKING DAYS, JANUARY 1963 TO DECEMBER 1972

	Consecutive wet working days					
	1	2	3	4	5	6
January	84	29	11	4	0	0
February	62	24	10	4	2	1
March	63	23	8	1	0	0
April	58	19	8	3	1	0
May	70	20	7	1	0	0
June	58	21	8	3	1	0
July	42	7	1	0	0	0
August	51	14	2	0	0	0
September	54	21	7	2	0	0
October	60	17	6	1	0	0
November	75	30	14	9	6	3
December	74	24	10	5	4	3
Total	751	249	92	33	14	7

Figure 1 shows the frequency distribution of the annual cumulative totals of single wet working days. The distribution is well scattered and not normal, as some 70 per cent of the totals are above the mean annual value.

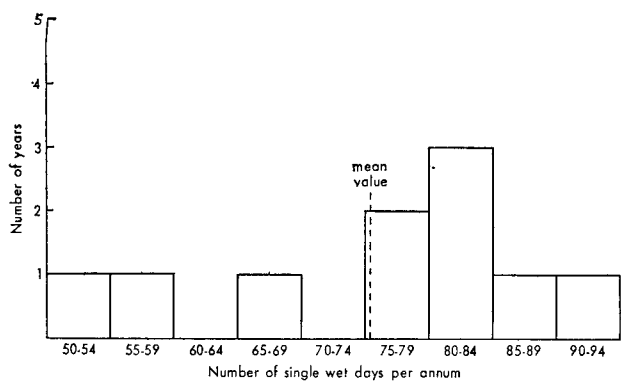


FIGURE 1—FREQUENCY DISTRIBUTION OF ANNUAL CUMULATIVE TOTALS OF SINGLE WET DAYS

Figure 2 shows the frequency distribution of the annual cumulative totals of pairs of consecutive wet working days. This shows a more even distribution, but with a high proportion concentrated in the extreme values.

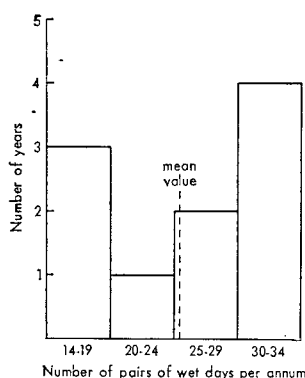


FIGURE 2—FREQUENCY DISTRIBUTION OF ANNUAL CUMULATIVE TOTALS OF PAIRS OF WET DAYS

TABLE III—CUMULATIVE AVERAGES OF CONSECUTIVE WET WORKING DAYS, JANUARY 1963 TO DECEMBER 1972

	Consecutive wet working days					
	1	2	3	4	5	6
January	8.4	2.9	1.1	0.4	0.0	0.0
February	6.2	2.4	1.0	0.4	0.2	0.1
March	6.3	2.3	0.8	0.1	0.0	0.0
April	5.8	1.9	0.8	0.3	0.1	0.0
May	7.0	2.0	0.7	0.1	0.0	0.0
June	5.8	2.1	0.8	0.3	0.1	0.0
July	4.2	0.7	0.1	0.0	0.0	0.0
August	5.1	1.4	0.2	0.0	0.0	0.0
September	5.4	2.1	0.7	0.2	0.0	0.0
October	6.0	1.6	0.6	0.1	0.0	0.0
November	7.5	3.0	1.4	0.9	0.6	0.3
December	7.4	2.4	1.0	0.5	0.4	0.3
Annual mean	75.1	24.9	9.2	3.4	1.4	0.7
Annual standard deviation	12.61	6.34	3.90	2.01	1.50	1.18
Monthly mean	6.3	2.1	0.8	0.28	0.12	0.06

Results

Average annual data. In the period under review Table III shows that there were on average:

75 wet working days in each year (lowest total 50, highest total 92) with a standard deviation of 12.6,

25 pairs of wet days in each year (lowest 14, highest 33) with a standard deviation of 6.3,

9 trios of wet days in each year (lowest 2, highest 14) with a standard deviation of 3.9,

3 quartets of wet days in each year,

1 quintet of wet days in each year,

1 sextet of wet days in seven years out of 10, but really concentrated in two unusually prolonged wet spells when two 8-day sequences occurred.

Average monthly data. Similarly there were on average, during the period under review:

6 wet working days in each month (lowest total 0, highest total 15),

2 pairs of wet days in each month (lowest 0, highest 8),

1 trio of wet days in each month,

1 quartet of wet days in every four months,

1 quintet of wet days in every nine months,

1 sextet of wet days in every 17 months.

Probabilities. For trying to complete a one-day project in dry weather (i.e. by definition less than one millimetre of rain per day) the likelihood is:

80 per cent if allotting only one day,

93 per cent if allotting two consecutive days,

97 per cent if allotting three consecutive days,

or, to put it another way, the chance of rain preventing completion is:

4 to 1 against if only one day is allotted to a task,

15 to 1 against if two consecutive days are allotted,

40 to 1 against if three consecutive days are allotted.

Discussion. There were spells of four wet working days in all but one of the 10 years examined; and two sequences of eight wet working days were recorded, one in November and the other in December of a different year.

June had eight occurrences of three consecutive wet days, whereas only one occurred in July. This rather surprising feature may be due to the relatively short period under examination. Apart from this, the cumulative totals show some increase in the period November–January, with about 20 per cent less in the spring and summer months compared with the remainder of the year (winter and autumn). July and August show a much higher proportion of single wet working days, which suggests a convective type of rainfall with the wet period probably concentrated in a short part of the working day.

In general, the longest wet spells, apart from an isolated occasion in June, are confined to the months November–April.

The cumulative averages reveal a marked increase over the equivalent values for London Weather Centre. However, taking into account the higher annual rainfall of the Southampton area, most of the monthly averages are increased by a similar ratio. The main exception is January, with almost twice the average number of wet working days, and one day out of four likely to be a wet one. Over the whole year, the odds of 6 to 1 against rain preventing completion of a one-day project in London, if allotting only a single day, are reduced to 4 to 1 for the Southampton area.

OBITUARY

It is with regret that we have to record the death of Mr. G. A. Samuel, Senior Scientific Officer, Met O 6, on 17 August 1974.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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